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Terminal Ballistics Studies

(TITLE UNCLASSIFIED)

by

Robert J. Denington

Contract No. AF 08(616)-77

prepared by...

Case Institute of Technology
University Circle
Cleveland 6, Ohio

for...

AIR PROVING GROUND CENTER

AIR RESEARCH AND DEVELOPMENT COMMAND, UNITED STATES AIR FORCE

EGLIN AIR FORCE BASE, FLORIDA

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February 1958

PROJECT DOAN BROOK

TECHNICAL MEMORANDUM NO. 20

TERMINAL BALLISTICS STUDIES

(Title Unclassified)

by

Robert J. Denington

CASE INSTITUDE OF TECHNOLOGY

UNIVERSITY CIRCLE

CLEVELAND 6, OHIO

CONTRACT NO. AF 08(616)-77

Prepared for the Air Proving Ground Center
Air Research and Development Command, USAF
Eglin Air Force Base, Florida

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PREFACE

Project Doan Brook was established in May 1951 under Contract No. 33(038)-24667 between Case Institute of Technology and the United States Air Force. A new contract, AF 08(616)-77, was negotiated in September 1956. The terminal ballistics studies considered in this report constitute an important phase of the larger Project objective of designing and developing an aerial land-mine case that will penetrate the earth and remain buried after being dropped from an aircraft at a low impact angle.

Except for the title, this report is classified CONFIDENTIAL in its entirety, in accordance with AFR-205-1, par 30b, because of the nature and potential military application of the research work presented herein.

ABSTRACT

This report is concerned with five series of terminal ballistics tests conducted with spheres, cylindrical missiles, and scale models. Generally, the tests were aimed at determining how the ricochet and penetration characteristics of a missile are affected by such factors as the impact velocity, impact angle, soil type, and physical and geometrical properties of the missile. The results obtained and reported herein have aided immeasurably in the larger Project Doan Brook objective of designing and developing an aerial land-mine case that will penetrate the earth and remain buried after being dropped from an aircraft at a low impact angle.

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SECTION I. INTRODUCTION

GENERAL

An important phase of the research and development work of Project Doan Brook has consisted of terminal ballistics tests to study the ricochet and penetration characteristics of spherical missiles and cylindrical scale models into cohesive and noncohesive soils. Data obtained from these experiments has proved useful in predicting the terminal trajectories of certain missile types, i.e., the path the missile takes from the time of earth impact until it assumes its final resting position. In this manner, the terminal ballistics studies have aided immeasurably in the larger Project objective of designing and developing the C-3 aerial land-mine case that will penetrate the earth and remain buried after being dropped from an aircraft at a low impact angle. One C-3 version -- designated the MJ-1 mine case by the Air Force -- is now in the production-engineering stage.

Generally, the terminal ballistics tests have been aimed at determining how the ricochet and penetration characteristics of a missile are affected by such factors as impact velocity, impact angle, soil type, and physical and geometrical properties of the missile. A good part of the work has already been reported in previously published technical memoranda (Ref. 1 through 7).

This report is concerned with five series of tests conducted with 0.356-in.-diameter spheres and with 1.367- and 0.356-in.-diameter cylindrical missiles and scale models. Specially constructed launchers were used to fire these missiles into noncohesive sand soil and into cohesive clay and cemented sand blocks. The launching equipment, testing methods, and data collection procedures have already been described in previous Project Doan Brook reports (Ref. 5, pp. 2-17 and 37-45; Ref. 6, pp. 2-6; and Ref. 7, pp. 2-9). Here the main emphasis is on the test

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objectives, data analyses, and results and conclusions.

CRITICAL ANGLE

In order to study the effect of various parameters on the ricochet tendencies of a missile under controlled conditions, and in order to express this effect quantitatively, a reference termed the critical angle or Θ_{crit} has been selected; this reference is defined as the impact angle at which a particular missile shape will ricochet 50 percent of the time and penetrate 50 percent of the time.

The basic procedure used to determine Θ_{crit} consists of first determining the range of angles at which both ricochet and penetration occurs, and then studying a missile's behavior at several angles within this range. Ordinarily, 16 shots are made at each of three or more angles between (1) the angle where ricochets equal 100 percent and penetrations equal zero percent and (2) the angle where ricochets equal zero percent and penetrations equal 100 percent.

After each shot, a record is made of the missile's impact velocity, its final resting position relative to the soil's surface, and whether it penetrated (P), ricocheted (R), or broached (B). The term penetration means that the entire missile came to rest below the orginal level of the soil; broach means that part of the missile was above the original sand level; ricochet means that the missile left its crater and landed beyond the crater limits. Although ricochets and broaches were recorded separately during the tests, they were combined in the final data and classified as nonpenetrations in establishing Θ_{crit}.

MODELING LAWS

Modeling laws, derived and verified in earlier Project Doan Brook publications (Ref. 5 and 8), were used as a basis for designing the cylindrical models considered in this report. Briefly, these laws are summarized as follows:

1. There must be complete geometrical similarity between the scale model and the full-size missile.

2. $W_m = \left(\frac{D_m}{D_f}\right)^3 W_f$

3. $I_m = \left(\frac{D_m}{D_f}\right)^5 I_f$

4. $V_m = V_f$

where W = weight, D = diameter, I = moment of inertia about the transverse axis through the center of gravity, V = impact velocity, the subscript m refers to the scale model, and the subscript f refers to the full-size missile.

SECTION II

EFFECTS OF MISSILE CHARACTERISTICS ON CRITICAL ANGLE

GENERAL

The purpose of the tests described in this section was to determine how θ_{crit} is affected by four missile characteristics: (1) weight, (2) length, (3) moment of inertia, and (4) location of center of gravity. The testing procedure is similar to that of an earlier test series, in which the objective was to study the effects of certain missile parameters on the length of penetration of missiles in sand (Ref. 6).

In order to standardize the effect on θ_{crit} of factors other than the four properties being investigated, all the tests were conducted within the same velocity range (400 to 500 fps), in identical soil, and with missiles of the same diameter (1.367 in.) and exterior geometry. Each of the test missiles was fired approximately 60 times into dry, noncohesive foundry sand, known commercially as Portage 40-60 sand.

The comparative properties of the various test missiles are shown in Table 1. A blunt-nosed missile, referred to as the C-5, was used as a standard (see Fig. 1). All the other missiles were similar to the C-5 except in the particular property or properties being tested. The C-5 was chosen as a standard because of its greater stability compared to that of a conical-nosed or ogive-nosed missile, and also because measurable changes in its relatively high θ_{crit} could be obtained by varying the missile properties.

The general procedure for determining the effects of the four missile properties was to vary the parameter being studied and to hold the remaining parameters constant. While it was not possible to maintain exact constancy, the slight variations were not sufficient to affect the test results significantly.

TABLE 1. PHYSICAL PROPERTIES OF TEST MISSILES

Missile	Weight (lb)	Moment of Inertia (in. lb sec^2)	Length (in.)	Location of Center of Gravity from Nose (in.)
C-5	0.708	0.00581	5.468	2.60
W-1	1.425	0.00590	5.468	2.60
W-2	0.435	0.00538	5.468	2.60
W-3	0.994	0.00595	5.468	2.48
W-4	2.375	0.01609	5.468	2.61
L-1	0.684	0.00563	8.000	3.77
L-2	0.695	0.00526	4.300	2.08
I-1	0.691	0.00885	5.468	2.54
I-2	0.691	0.00244	5.468	2.60
G-1	0.676	0.00530	5.468	1.72
G-2[a]	0.676	0.00530	5.468	3.74
G-3	0.701	0.00691	5.468	2.13
G-4[b]	0.701	0.00691	5.468	3.33
G-5[c]	0.708	0.00579	5.468	2.87

[a]Same as missile G-1, but fired in reverse.
[b]Same as missile G-3, but fired in reverse.
[c]Same as missile C-5, but fired in reverse.

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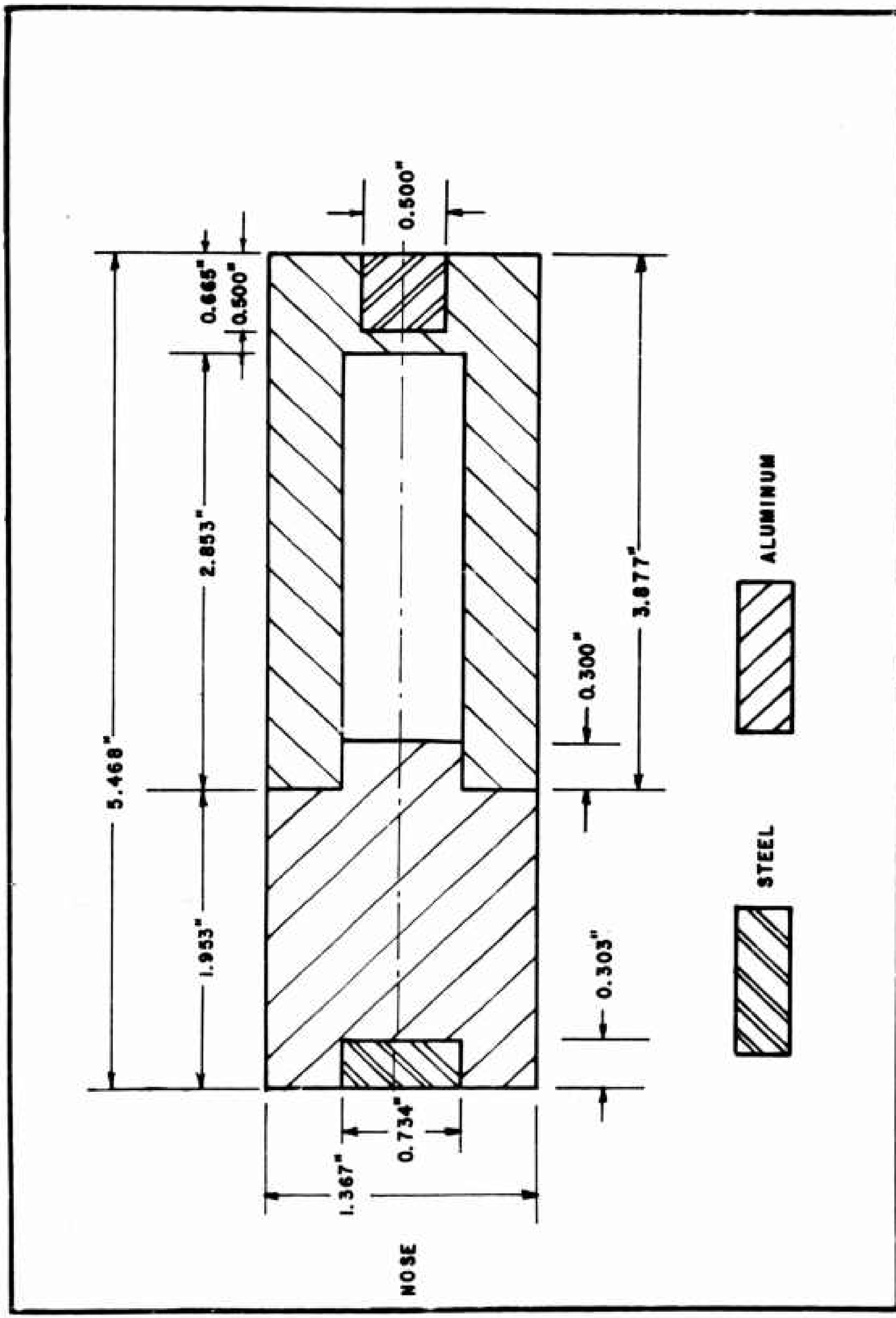

Fig. 1: C-5 Missile

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1. Weight -- Four missiles were constructed, termed W-1, W-2, W-3, and W-4 in Table 1, in which the weight was varied. An exception was the W-4, in which both weight and moment of inertia were changed to produce an extreme condition.

2. Length -- Two missiles were constructed, termed L-1 and L-2. Since it was impractical to vary the length of these models and still maintain a constant distance between the nose and the location of the center of gravity, the following ratio was held constant:

$$\frac{\text{distance from center of gravity to nose}}{\text{total length of missile}}$$

3. Moment of Inertia -- Two missiles were constructed, designated I-1 and I-2. In one model, the moment of inertia was lower than that of the C-5 standard, and in the other it was higher.

4. Location of Center of Gravity -- Two missiles were constructed in which the distance between the center of gravity and the nose was varied. Each of these was fired in a forward and reverse position. The standard C-5 missile was also fired for this series, thus making a total of five changes in the location of center of gravity. The missiles are designated as G-1, G-2, G-3, G-4, and G-5.

RESULTS AND CONCLUSIONS

The results presented apply only to the particular type of blunt-nosed missile used in these tests. It is to be expected that with missiles of other nose shapes, where θ_{crit} is usually much higher, the properties studied here may have much larger effects on θ_{crit}. Moreover, the results are only known to apply in sand soils for a limited range of impact velocities from about 400 to 500 fps.

Dependence of θ_{crit} on Weight

As is shown in Table 2A and Fig. 2, variation in θ_{crit} was inverse to variation in the missile's weight. Moreover, Fig. 2, a plot of θ_{crit} against missile weight, indicates that very little further decrease in

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TABLE 2

(A) DEPENDENCE OF θ_{CRIT} ON MISSILE WEIGHT

Missile	Weight (lb)	Change in Weight (%)	θ_{crit} (deg)
C-5	0.708	-	17
W-1	1.423	+100.98	13
W-2	0.435	-38.56	22
W-3	0.994	+40.39	14
W-4	2.375	+235.45	13

(B) RICOCHET AND PENETRATION DATA

Missile	Impact Angle (deg)	No. of Penetrations	No. of Ricochets	No. of Broaches	Nonpenetrations (%)
C-5	16	4	7	5	75.0
	17	10	3	3	37.5
	17	6	6	4	62.5
W-1	11	1	14	1	93.7
	13	5	9	2	68.7
	13	8	7	1	50.0
	15	13	3	0	18.7
W-2	19	1	13	2	93.7
	21	2	7	7	87.5
	22	3	12	1	81.2
	23	11	2	3	31.2
	25	14	1	1	12.5
W-3	13	2	13	1	87.5
	15	12	1	3	25.0
	17	16	0	0	0.0
W-4	11	5	11	0	68.7
	12	6	10	0	62.5
	14	10	6	0	37.5

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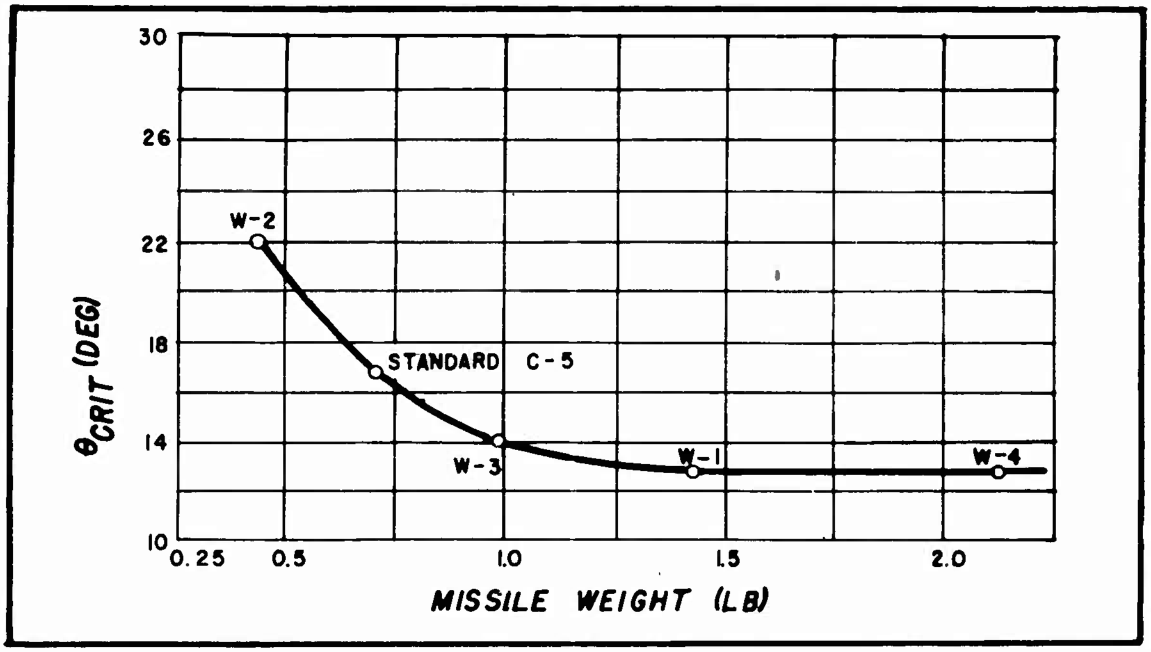

Fig. 2: Dependence of Critical Angle on Missile Weight

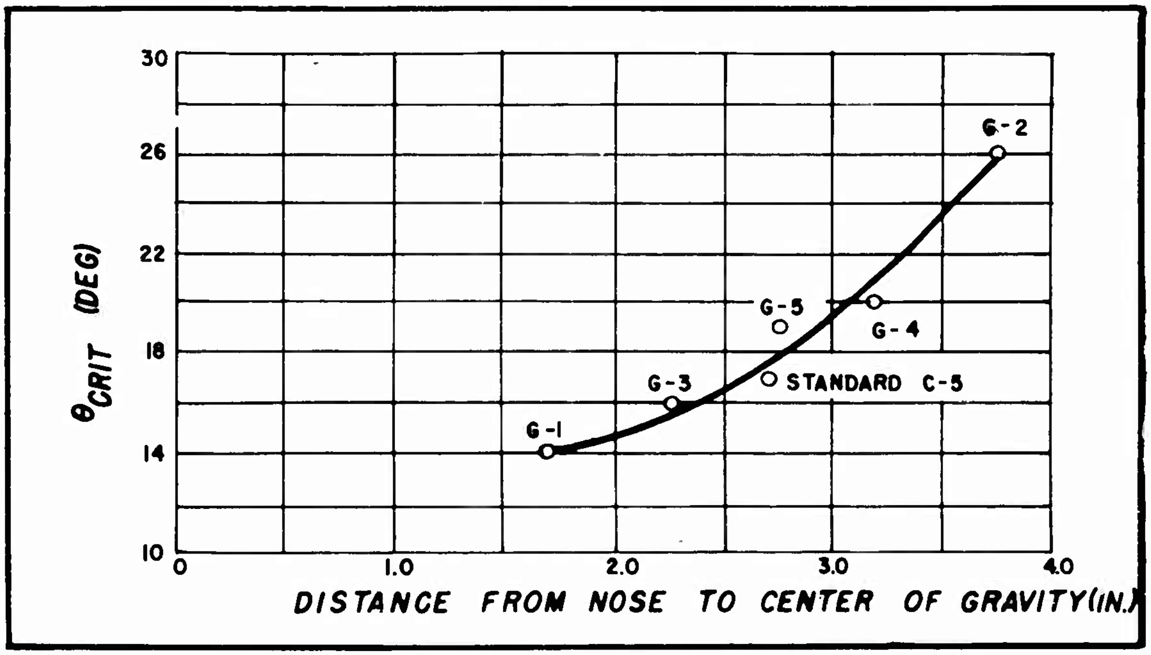

Fig. 3: Dependence of Critical Angle on Location of Center of Gravity

Θ_{crit} would result from increasing weight above a certain value. This conclusion was confirmed by tests on missile W-4, whose weight and moment of inertia were both greatly increased.

Dependence of Θ_{crit} on Length

The results summarized in Table 3A indicate that no measurable change in Θ_{crit} occurred when the length is either increased or decreased, provided that the following ratio was held constant:

$$\frac{\text{distance from center of gravity to nose}}{\text{total length of missile}}$$

Dependence of Θ_{crit} on Moment of Inertia

The results are presented in Table 4A. They indicate that relatively small changes in moment of inertia result in small changes in Θ_{crit}, and that an increase in moment of inertia causes a decrease in Θ_{crit}.

Dependence of Θ_{crit} on Location of the Center of Gravity

The results, tabulated in Table 5A and plotted in Fig. 3, show that the location of the center of gravity is important in determining Θ_{crit}. Moving the center of gravity forward toward the nose of the missile produces a decrease in Θ_{crit}; and moving the center of gravity back toward the tail of the missile causes an increase in Θ_{crit}.

A complete recapitulation of all the data relative to the missiles discussed in this section is found in Tables 2B, 3B, 4B, and 5B.

TABLE 3

(A) DEPENDENCE OF θ_{CRIT} ON MISSILE LENGTH

Missile	Length (in.)	Change in Length (%)	θ_{crit} (deg)
C-5	5.468	-	17
L-1	8.000	+46.30	17
L-2	4.300	-21.36	17

(B) RICOCHET AND PENETRATION DATA

Missile	Impact Angle (deg)	No. of Penetrations	No. of Ricochets	No. of Broaches	Nonpenetrations (%)
C-5	16	4	7	5	75.0
	17	10	3	3	37.5
	17	6	6	4	62.5
L-1	14	0	14	2	100.0
	15	0	16	0	100.0
	15	9	1	6	43.7
	16	9	2	5	43.7
	16	4	8	4	75.0
	17	9	0	7	43.7
	18	10	0	6	37.0
	20	16	0	0	0.0
L-2	13	0	16	0	100.0
	15	2	11	3	87.5
	17	7	8	1	56.2
	19	15	0	1	6.0

TABLE 4

(A) DEPENDENCE OF θ_{CRIT} ON MOMENT OF INERTIA

Missile	Moment of Inertia (in. lb sec^2)	Change in Moment of Inertia (%)	θ_{crit} (deg)
C-5	0.00581	-	17
I-1	0.00885	+52.32	17
I-2	0.00244	-58.00	18

(B) RICOCHET AND PENETRATION DATA

Missile	Impact Angle (deg)	No. of Penetrations	No. of Ricochets	No. of Broaches	Nonpenetrations (%)
C-5	16	4	7	5	75.0
	17	10	3	3	37.5
	17	6	6	4	62.5
I-1	14	0	16	0	100.0
	15	2	10	4	87.5
	17	11	1	4	31.2
	18	15	0	1	6.0
	19	16	0	0	0.0
	20	16	0	0	0.0
I-2	15	0	16	0	100.0
	16	0	13	3	100.0
	17	6	6	4	62.5
	18	4	4	8	75.0
	19	15	1	0	6.2

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TABLE 5

(A) DEPENDENCE OF Θ_{CRIT} ON LOCATION OF CENTER OF GRAVITY

Missile	Distance of Center of Gravity from Nose (in.)	Change in Location of Center of Gravity (%)	Θ_{crit} (deg)
G-1	1.72	-35.34	14
G-2	3.74	+40.60	26
G-3	2.26	-15.04	16
G-4	3.21	+20.67	20
G-5	2.81	+05.63	19

(B) RICOCHET AND PENETRATION DATA

Missile	Impact Angle (deg)	No. of Penetrations	No. of Ricochets	No. of Broaches	Nonpenetrations (%)
G-3	13	0	13	3	100.0
	15	7	0	9	56.0
	17	11	0	5	31.2
G-4	18	3	13	0	81.2
	18	5	9	2	68.7
	20	10	5	1	37.5
	20	8	6	2	50.0
	22	7	5	4	50.0
	24	13	2	1	18.7
G-5	18	13	0	3	18.7
	17	2	10	4	87.5
	19	8	5	3	50.0
	21	12	3	1	25.0
G-1	11	0	8	0	100.0
	12	8	8	0	50.0
	13	2	4	10	87.5
	15	13	0	3	18.7
	17	16	0	0	0.0
G-2	15	0	16	0	100.0
	17	2	14	0	87.5
	19	0	13	3	100.0
	21	1	13	2	93.7
	25	6	6	4	62.5

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SECTION III

EFFECT OF VARIOUS MISSILE SHAPES ON CRITICAL ANGLE

GENERAL

Included in this section is a compilation of ricochet and penetration data, and the conclusions derived from these data, for three missile types. The basic objective of the tests was to determine the effect of each geometrical shape on θ_{crit}.

The physical properties of the test missiles are presented in Table 6. All had a standard diameter of 1.367 in. and all were fired into Portage 40-60 sand at velocities ranging from approximately 300 to 600 fps.

TABLE 6

PHYSICAL PROPERTIES OF TEST MISSILES

Missile	Weight (lb)	Length (in.)	Moment of Inertia (in. lb sec^2)	Location of Center of Gravity from Nose (in.)
C-3	1.016	8.202	0.017	3.965
C-3A	1.016	8.202	0.017	3.965
C-3B	1.016	8.202	0.017	3.965
C-3C	1.016	8.202	0.017	3.965
C-3, M-4	0.990	7.030	0.012	3.420
C-7	1.040	9.560	0.016	3.638
L-3	1.560	16.030	0.020	7.540
HEP	0.266	3.780	-	1.469

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The missile types are as follows:

1. Five modifications of the C-3 blunt-nose, cylindrical missile developed by Project Doan Brook. These missiles are designated: C-3A, C-3B, C-3C, C-3 Mod 4, and C-7.
2. The L-3 blunt-nose cylinder having a relatively higher weight, moment of inertia, and L/D ratio than the C-3.
3. The High Explosive Plus (HEP) bomb, an Air Force experimental, blunt-nose shape.

RESULTS AND CONCLUSIONS

The ricochet and penetration data of the missiles considered in this section are presented in Table 7. Each missile type is treated separately.

C-3 Modifications

Terminal ballistics studies have resulted in the design and development of the C-3, blunt-nose, cylindrical model (see Fig. 4), which satisfies the Project Doan Brook requirement of successful earth penetration at a low impact angle. The design of a full-scale experimental model of the C-3, however, indicated that it might be necessary to deviate from the simple design of the scale model. In order to provide increased strength at the nose and tail plates, it was suggested that the full-scale design consist of a cylinder with forgings welded to each end. Forgings, in turn, require a slight taper to facilitate removal of the units from the forging dies. Thus, the use of forgings without considerable machining would change the exterior shape of the full-scale missile.

With this possibility in mind, it was decided to model the C-3A, C-3B, and C-3C missiles with tapers comparable with those that might result from forging in order to determine the effect of this change on θ_{crit}. The C-3A model had a 2.5-deg taper on the tail; the C-3B, a 5-deg taper on the nose; and the C-3C, a 2.5-deg taper on the nose. The results, shown in Table 7, did not indicate any deviation from the normal 14-deg critical angle of the C-3.

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TABLE 7. RICOCHET AND PENETRATION DATA

Missile	Impact Angle (deg)	Average Velocity (fps)	No. of Shots	No. of Penetrations	No. of Ricochets	No. of Broaches	Nonpenetrations (%)	θ_{crit} (deg)
C-3	12	397	16	0	16	0	100.00	14
	13	359	16	0	16	0	100.00	
	14	330	16	10	0	6	37.50	
	16	306	16	13	0	3	18.75	
	18	427	16	16	0	0	0.00	
C-3A	15	461	16	10	2	4	37.50	14
	17	414	16	15	1	0	6.25	
C-3B	15	323	16	9	7	0	43.75	14
	17	370	16	16	0	0	0.00	
C-3C	15	500	16	6	10	0	62.50	14
C-3, M-4	15	502	16	2	11	3	87.50	18
	17	488	16	7	8	1	56.25	
	19	460	16	16	0	0	0.00	
C-7	15	418	16	1	11	4	93.75	18
	17	420	16	3	9	4	81.25	
	19	427	16	12	2	2	25.00	
	21	416	16	15	0	1	6.25	
L-3	10	362	8	0	8	0	100.00	11
	12	292	16	16	0	0	0.00	
HEP	24	[a] 600 ± 50	16	0	1	15	100.00	28
	28		16	7	9	0	56.25	
	30		16	11	5	0	31.25	

[a] Estimated velocity, based on weight of missile, barrel, fuel, and pressure pin.

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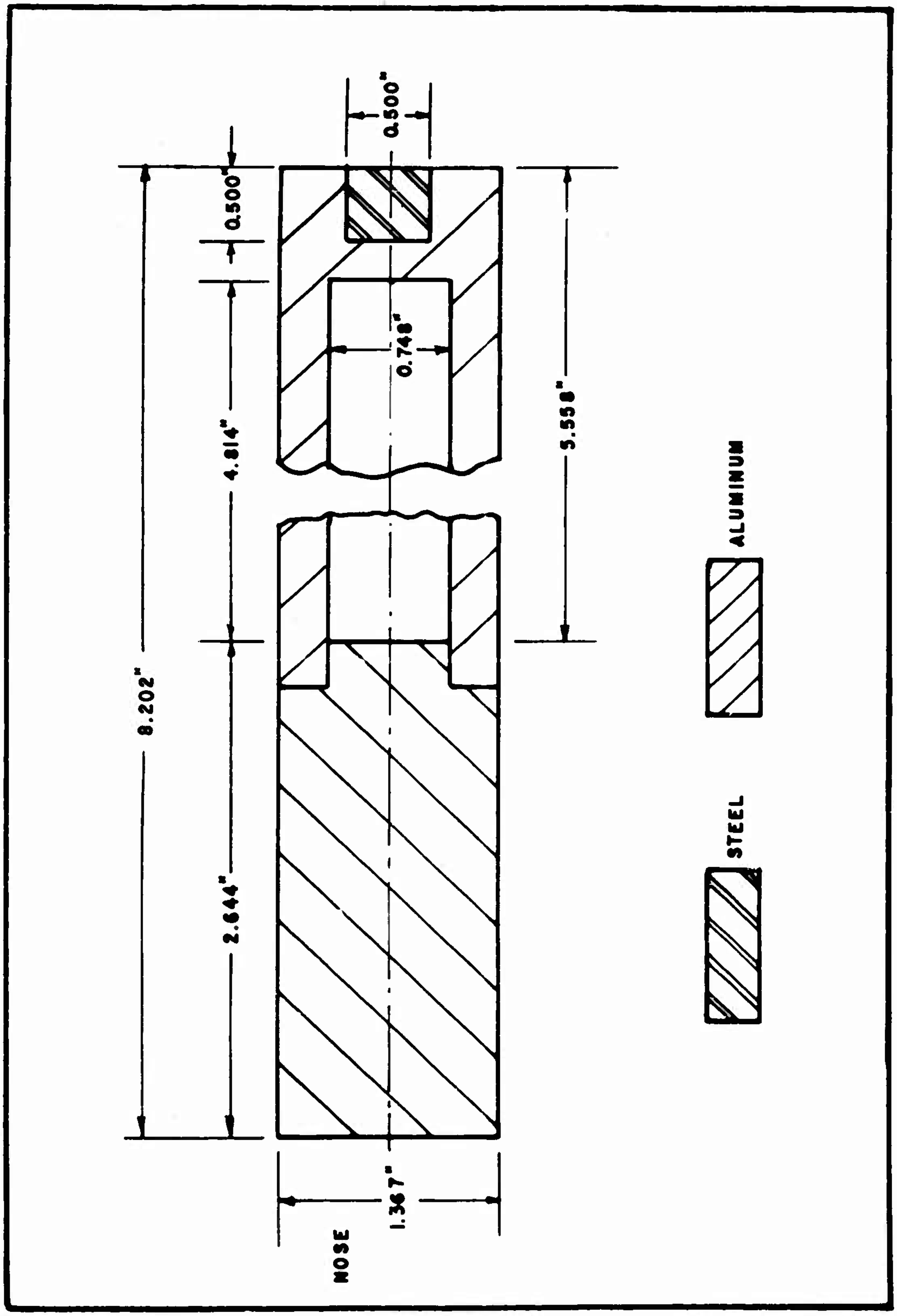

Fig. 4: C-3 Missile

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The C-3 Mod 4 missile (see Fig. 5) is a scale model of an experimental full-size model being constructed by Project Doan Brook. The full-size model utilizes a modified cylindrical section from the Mark 83 Mod 3 bomb case for the body. The cylindrical section was taken from the Mark 83 production line before the nose-forming operation but after the boatailing operation. This resulted in a case with an L/D ratio of 5.1 to 1 as compared with 6 to 1 for the other C-3 models.

The test results, shown in Table 7, indicate that the C-3 Mod 4 design has a θ_{crit} of 18 deg -- 4 deg higher than the C-3.

The Project Doan Brook MJ-1 air-laid mine case consists essentially of a blunt-nosed, cylindrical tube filled with explosive and a standard high-speed tail-cone and fin assembly which is bolted onto the rear plate. This tail-fin assembly is a hollow unit which adds 3 to 3.5 ft to the over-all length of the mine without adding to the payload or structural strength during the underground trajectory of the missile.

The model of the C-7 missile (see Fig. 6) represents an effort to utilize the empty tail-cone space by lengthening the case and fins directly to the case. Thus, a higher L/D ratio for the case is obtained, while the over-all length of the case and fins is kept relatively short. This provides a shorter, more efficient mine in terms of internal aircraft storage.

The test results with the C-7 model indicate a θ_{crit} of 18 deg, as compared with 14 deg for the C-3. The higher θ_{crit} may be due to the long tapered tail of over one-half the missile length. This tapered portion of the missile is probably not in contact with the surrounding soils during its underground trajectory. Less contact would reduce the resistance to angular rotation and thus could result in a higher θ_{crit}.

L-3 Missile

Previous studies have indicated (1) that the θ_{crit} of a missile can be lowered by increasing its weight and/or moment of inertia about its center of gravity (Section II of this report) and (2) that an increase in the L/D ratio, though not affecting the θ_{crit}, does increase the

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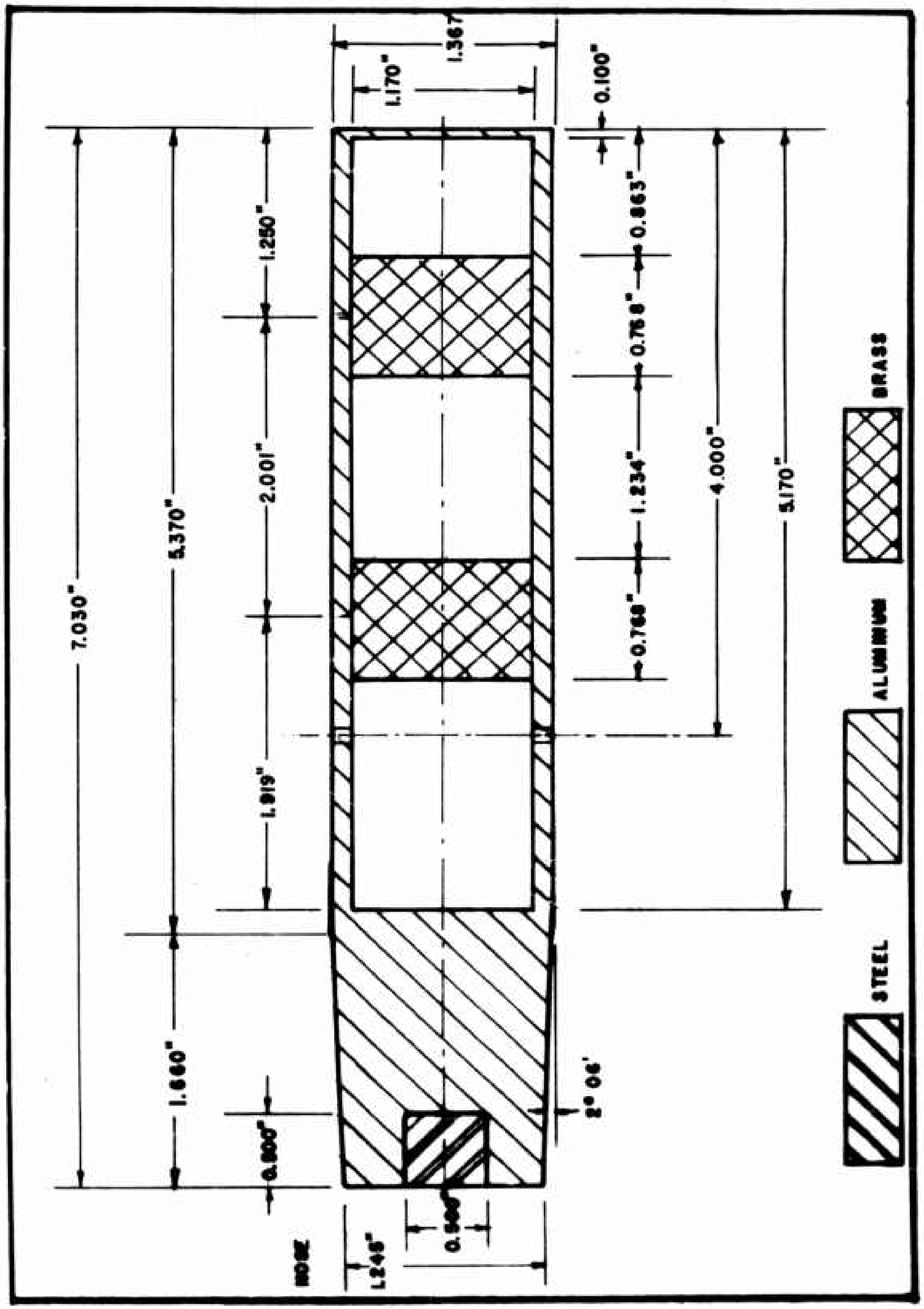

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Fig. 5: C-3 Mod 4 Missile

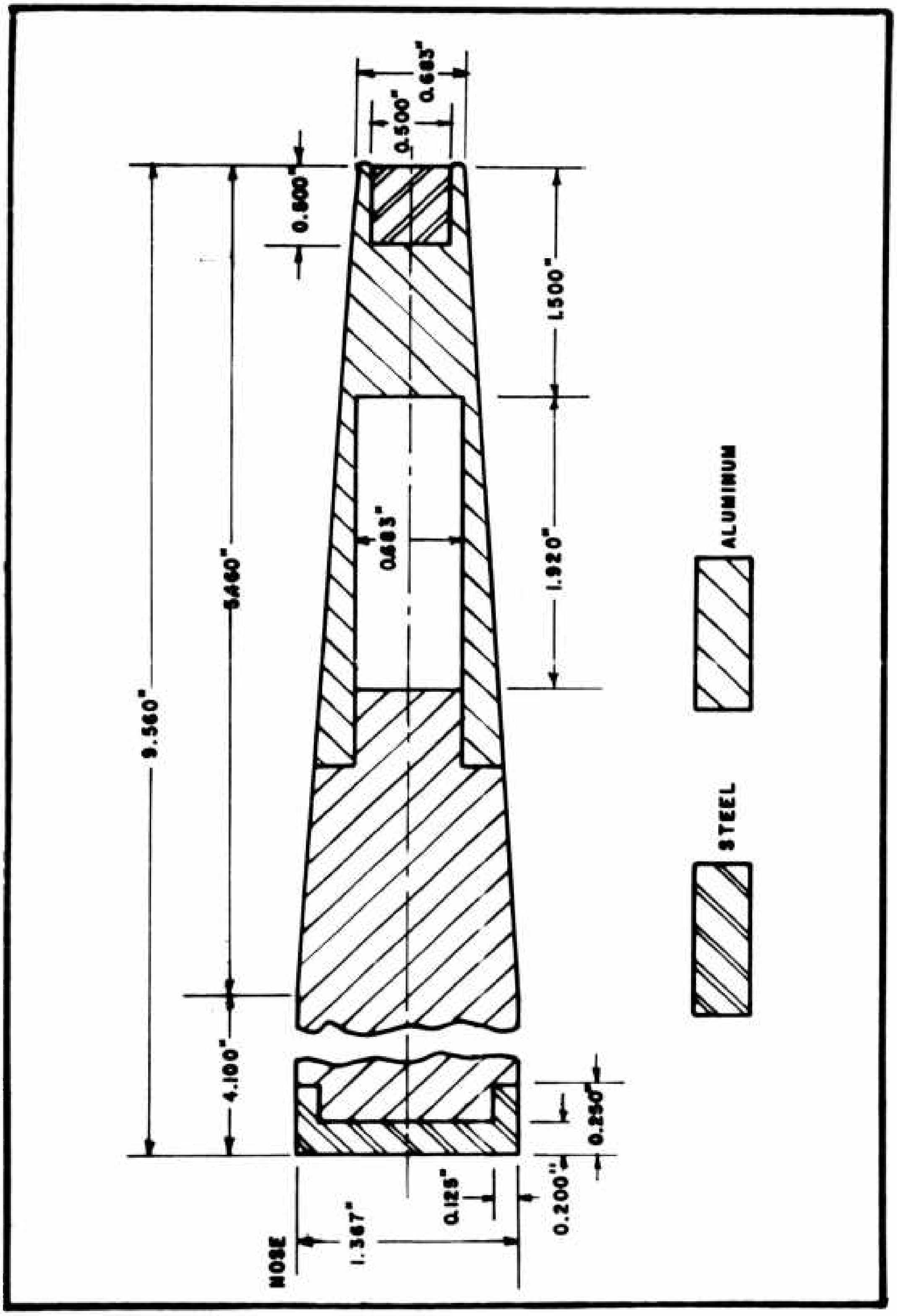

Fig. 6: C-7 Missile

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stability of the missile during its underground trajectory (Ref. 6).

The L-3 missile (see Fig. 7) -- having a relatively higher weight, moment of inertia, and L/D ratio than the C-3 -- was designed to test the validity of these conclusions. The results, shown in Table 7, indicate a θ_{crit} of 11 deg, the lowest obtained with any model in dry sand. The missile proved very stable and deviated only a relatively small amount from a straight trajectory. It should be observed, however, that the L-3 -- because of its relatively high L/D ratio -- is not too practical for manufacturing.

High Explosive Plus (HEP) Bomb Shape

The High Explosive Plus (HEP) bomb shape (see Fig. 8) was designed for aerodynamic stability when released from the bomb bay at high speeds. Drop tests, conducted with full-size HEP models at Wright-Patterson AFB, Dayton, Ohio (Ref. 9), indicated that the HEP shape possesses favorable release and separation characteristics. It proved less sensitive to bomb-bay turbulances than the conventional streamline bombs and, consequently, reduced the instability of a bomb when released from a bomb bay at high speeds. Because this shape has no tail cone or fin, it provides increased bomb-bay storage efficiency. The bomb has proven constant in flight. The case design is relatively simple and would not create high accuracy problems in manufacturing.

The model studies made with the HEP shape (see Table 7) indicate that the HEP model has a θ_{crit} of 28 deg. This figure is relatively high when compared with the 14-deg θ_{crit} of the C-3 missile, but it is reasonable when compared with the θ_{crits} obtained for the present standard Air Force bomb cases; namely, 31.6 deg (at 600 fps) for the 500-lb GP bomb and 34.0 deg (at 450 fps) for the 750-lb T-54 shape.

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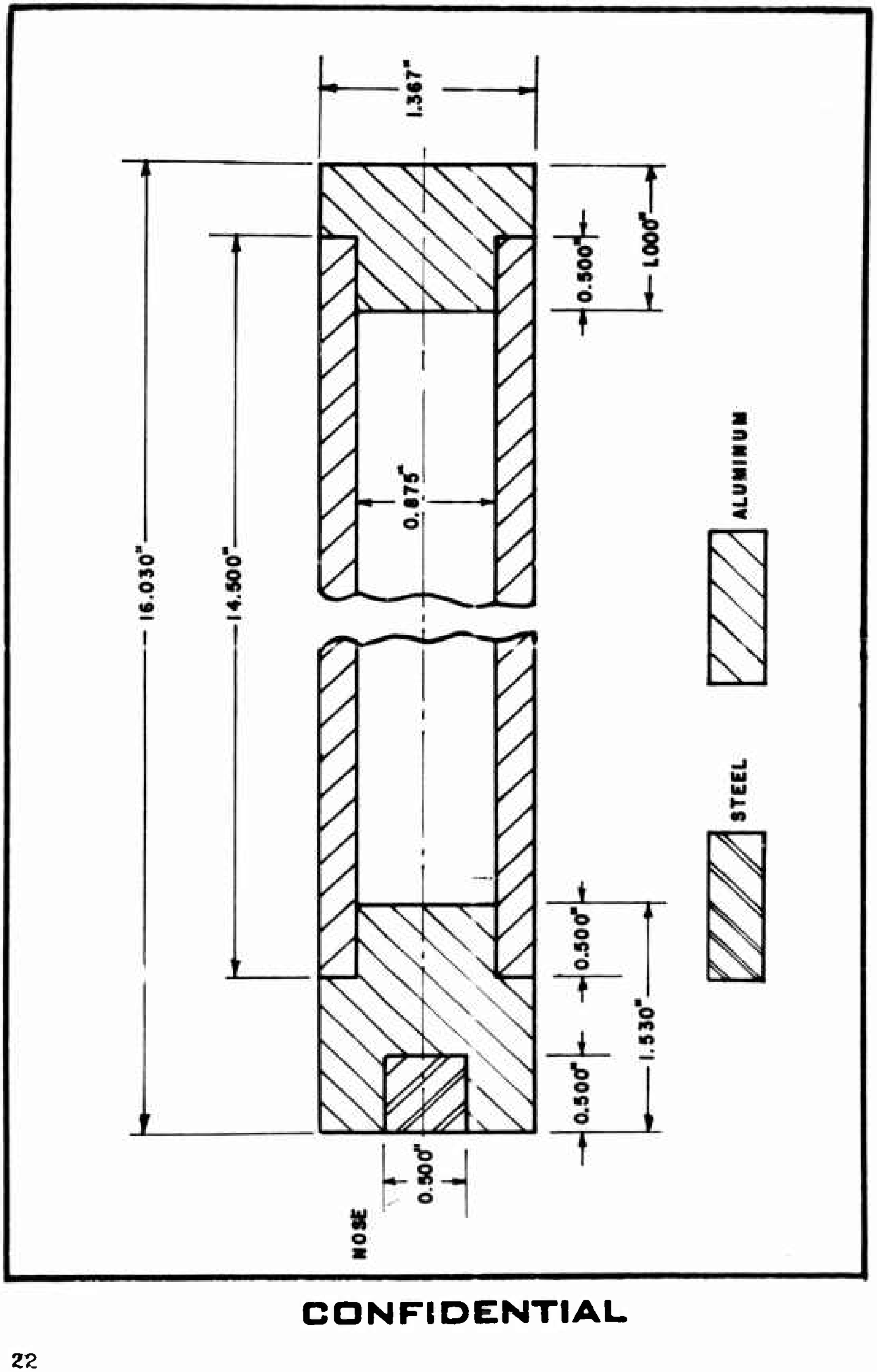

Fig. 7: L-3 Missile

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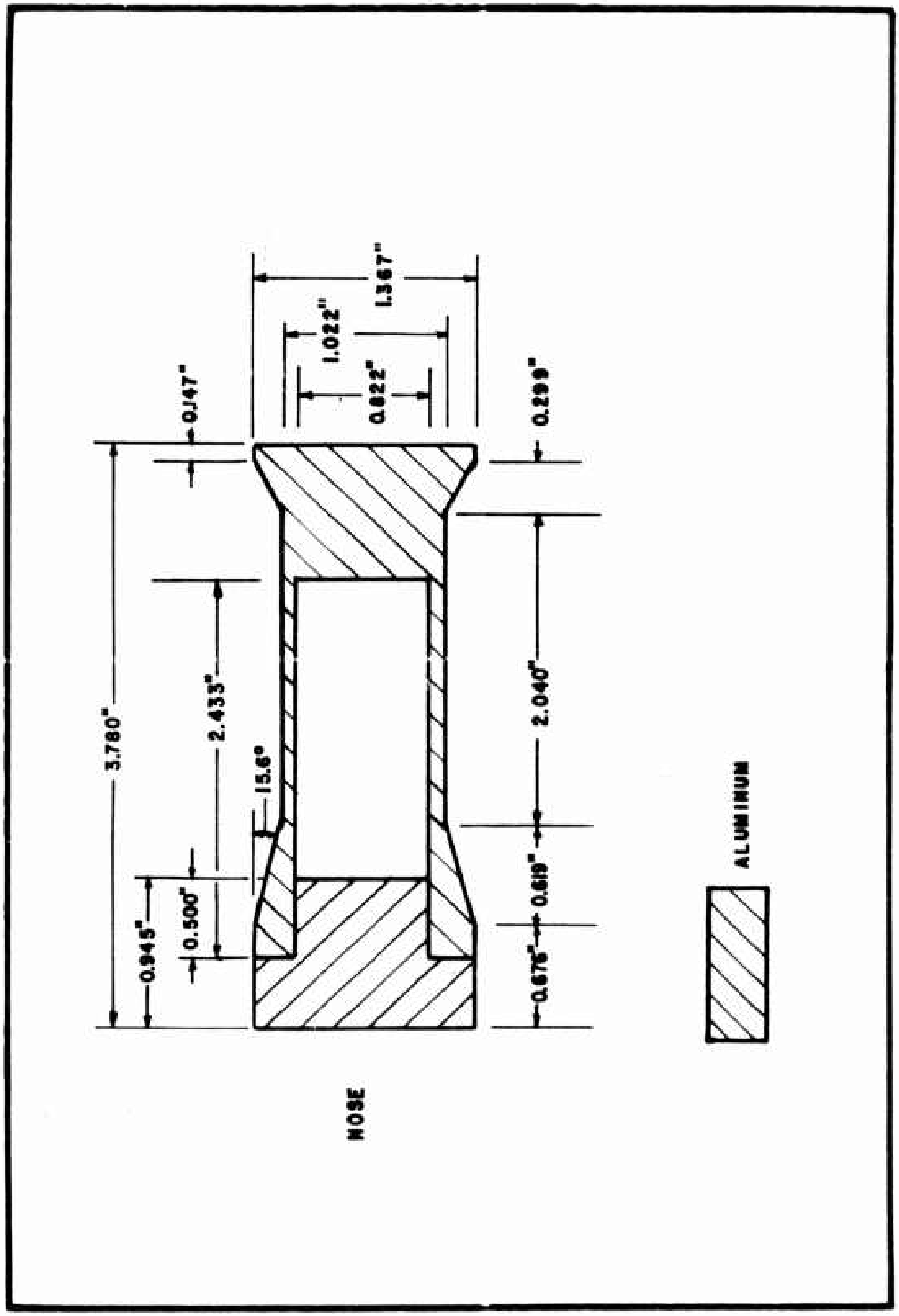

Fig. 8: HEP Bomb Shape

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SECTION IV

RICOCHET AND PENETRATION OF CYLINDRICAL MISSILES IN CLAY AND SAND SOILS

GENERAL

The experiments described in this section were aimed at studying the ricochet and penetration characteristics of cylindrical missiles in cohesive and noncohesive soils. Two specific objectives were:

1. To determine the effect of impact velocity, and missile nose shape, length, weight, and moment of inertia on θ_{crit}
2. To determine the effects of certain soil parameters on θ_{crit}

Four missiles (see Fig. 9 and Table 8), all having a diameter of 0.356 in., were fired into clay soils common to the Cleveland area and also into dry sand obtained from the Hoffman Foundry Supply, Cleveland. All the test missiles -- designated the S-3, S-4, S-5, S-6 -- had blunt noses except the S-6, which had a 90-deg conical nose.

TABLE 8. PHYSICAL PROPERTIES OF TEST MISSILES

Missile	Weight (lb)	Moment of Inertia (in. lb sec^2)	Location of Center of Gravity from Nose (in.)	Nose Shape
S-3	0.0142	6.21×10^{-6}	0.712	Blunt
S-4	0.0123	5.79×10^{-6}	0.692	Blunt
S-5	0.0178	18.1×10^{-6}	1.040	Blunt
S-6	0.0193	20.0×10^{-6}	0.536	Conical

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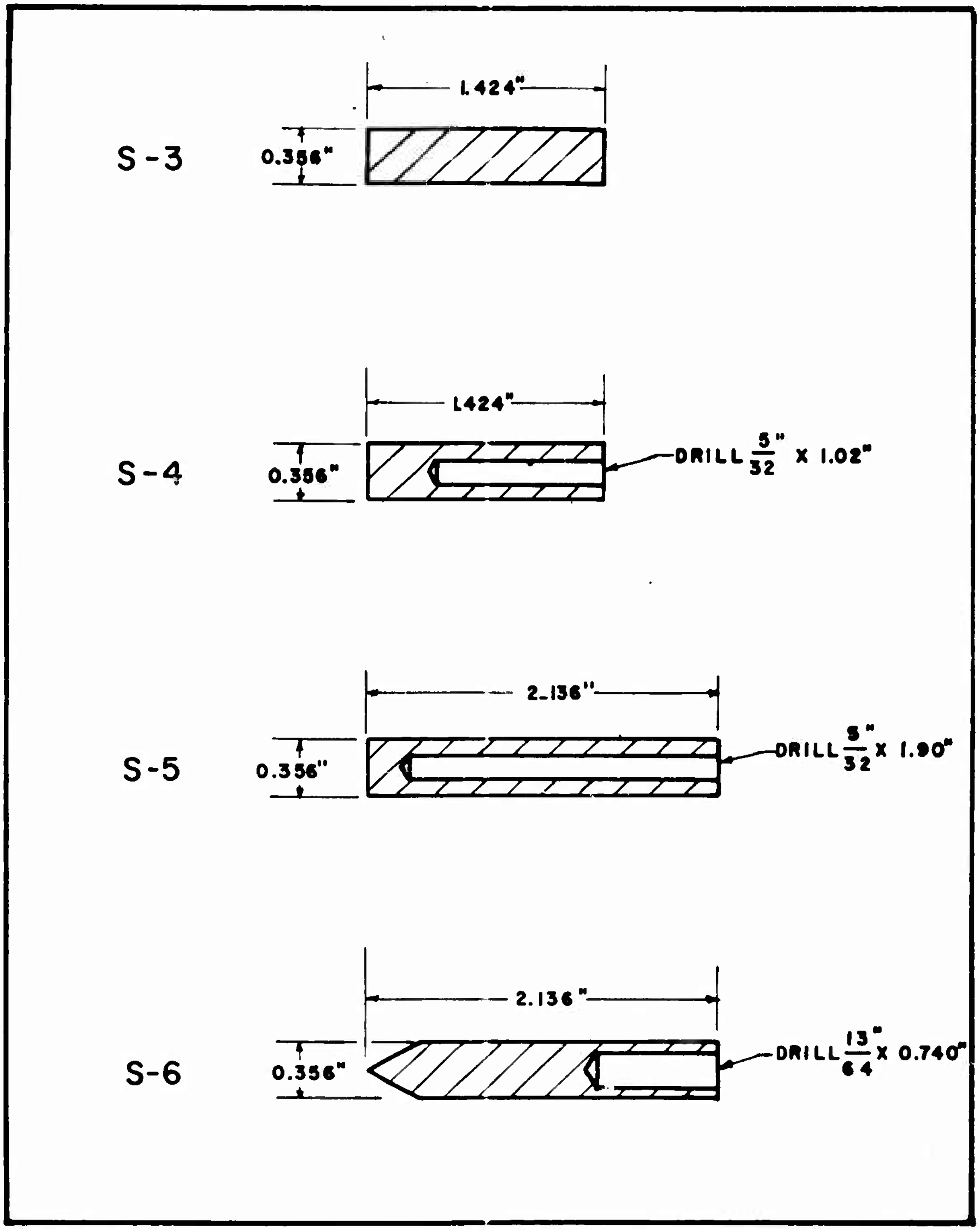

Fig. 9: S-3, S-4, S-5, S-6 Missiles

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The soil properties of the clay and sand soils are presented in Table 9. The tests with clay soils were performed at four sites, each offering a clay of unique composition. The designation of each clay type and its location is as follows:

Clay		Location
Neff	--	Off Euclid Ave., Euclid, O.
Chester	--	Off Walnut Ridge Rd., Chester, O.
Mentor	--	Mentor Headlands, O.
Auburn	--	Auburn, O.

The effective cohesion and angle of internal friction were determined for each clay soil by a series of tri-axial tests (explained in Ref. 7). The tri-axial test data for the soils invested in this report are included in Table 14 at the end of this section (beginning p. 36). The procedure for determining the other soil properties is also explained in Ref. 7.

RESULTS

All the clay-soil data for this test series are presented in Table 15 at the end of this section (beginning p. 38). The results are discussed in terms of how θ_{crit} is affected by impact velocity, missile nose shape, missile weight, length, moment of inertia, and the soil properties.

Effect of Impact Velocity

The S-3, S-4, and S-5 blunt-nosed missiles were used to study the effect of impact velocity on θ_{crit}. The results (see Table 10) indicate that, in dry sand, there is only a slight random change in θ_{crit} as the impact velocity is varied. In clay soils, however, θ_{crit} decreases as impact velocity decreases. As indicated by Fig. 10 (p. 32), this effect is keenly felt in velocity ranges lower than 800 fps, but is not too apparent in those ranges higher than 800 fps.

Effect of Nose Shape

The effect of missile nose shape on θ_{crit} is shown in Table 11.

TABLE 9. PROPERTIES OF CLAY AND SAND SOILS

Soils	Description	Effective Cohesion (psi)	Angle of Internal Friction (deg)	Bulk Density (lb/ft^3)	Moisture Content (% dry wt)	Liquid Limit (% Moisture Content)	Plastic Limit (% Moisture Content)
Neff	Medium, gray clay	19	35	126	17.5	42	22
Chester	Medium, yellow clay	12	28	126	22.3	37	22
Mentor	Soft, blue-gray clay	3	36	125	27	36	22
Auburn	Sandy, yellow clay	13	12	119	24.2	-	-
40-60 Sand	-	0	34	103	0	0	0

TABLE 10. EFFECT OF IMPACT VELOCITY ON Θ_{CRIT}

Missile	Soil	Velocity Range (fps)	Θ_{Crit} (deg)
S-5	Neff Clay	200-300	35-39
S-5	Neff Clay	460-555	14-15
S-5	Neff Clay	950-1110	9-11
S-4	Neff Clay	490-590	13-16
S-4	Neff Clay	910-1175	9-12
S-3	Neff Clay	510-600	12-14
S-3	Neff Clay	1110-1250	9-11
S-4	Sand	450-550	23-25
S-4	Sand	950-1050	24-26
S-5	Sand	450-550	17-18
S-5	Sand	950-1050	15-16

TABLE 11. EFFECT OF MISSILE NOSE SHAPE ON Θ_{CRIT}

Missile	Soil	Velocity Range (fps)	Nose Shape	Θ_{Crit} (deg)
S-6	Neff	425-525	Corical	17-19
S-5	Neff	460-555	Blunt	14-15
S-6	Dry Sand	500-600	Conical	19-21
S-5	Dry Sand	450-550	Blunt	17-18
S-6	Dry Sand	950-1050	Conical	16-17
S-5	Dry Sand	950-1050	Blunt	15-16

The S-5 and S-6 missiles used in this test are almost identical except for the nose shapes. The slight differences in weight and moment of inertia of the two missiles were too insignificant to affect the results. The data indicate that the conical-nosed missile has a slightly higher θ_{crit} than the blunt-nosed missile.

Effect of Length, Weight, and Moment of Inertia

The S-3, S-4, and S-5 missiles were used to study the effects of missile length, weight, moment of inertia on θ_{crit}. The S-3 and S-4 were similar as far as the three properties are concerned, but in the S-5 these characteristics were considerably higher (see Table 8). The results, presented in Table 12, do not show any consistent, measurable change in θ_{crit} in clay soils. In sand soils, however, the S-5 missile had a considerably lower θ_{crit} than the S-3 and S-4 missiles; on the basis of the observations made in Section II of this report, missile weight is probably the main factor in causing this variation.

Effect of Soil Properties

As indicated by Table 13, the properties of clay soils have only a very slight effect on θ_{crit}. However, the missiles fired into dry sand have a higher θ_{crit} than those fired into clay.

ANALYSIS AND CONCLUSIONS

Previously, tests were conducted by Project Doan Brook to determine the ricochet and penetration properties of steel spherical missiles in natural clay soils and dry sands (Ref. 7). Fig. 10 and 11 incorporate velocity vs θ_{crit} data obtained from these spherical missile tests with data for several cylindrical missiles described earlier in this report. Fig. 10 applies to clay soil and Fig. 11 to sand.

Dry sand soils having identical properties were used for both the spherical and cylindrical missile tests referred to in Fig. 11. The spherical and cylindrical missile tests employed the same type of clay (Neff), but the tests were conducted at different seasons of the year. As a result, the moisture content, cohesive strength, and density of the soils varied. The curves, therefore, should not be used to compare

TABLE 12. EFFECT OF MISSILE WEIGHT, LENGTH, AND MOMENT OF INERTIA ON θ_{CRIT}

Missile	Soil	Velocity Range (fps)	θ_{Crit} (deg)
S-3	Neff Clay	510-600	12-14
S-4	Neff Clay	490-590	13-16
S-5	Neff Clay	460-555	14-15
S-3	Neff Clay	1110-1250	9-11
S-4	Neff Clay	910-1175	9-12
S-5	Neff Clay	950-1110	9-11
S-4	Dry Sand	450-550	23-25
S-5	Dry Sand		17-18
S-3	Dry Sand	950-1050	22-24
S-4	Dry Sand		24-26
S-5	Dry Sand		15-16

TABLE 13. EFFECT OF SOIL PROPERTIES ON θ_{CRIT}

Missile	Velocity Range (fps)	Soil	θ_{Crit} (deg)
S-4	490-590	Neff Clay	13-16
S-4	400-600	Mentor Clay	14-16
S-4	450-550	Sand	23-25
S-4	910-1175	Neff Clay	9-12
S-4	1000-1400	Mentor Clay	14-16
S-4	950-1050	Sand	24-26
S-5	460-560	Neff Clay	14-15
S-5	400-600	Chester Clay	10-14
S-5	580-710	Auburn Clay	10-14
S-5	450-550	Sand	17-18
S-5	950-1110	Neff Clay	9-11
S-5	950-1050	Sand	15-16
S-3	1110-1250	Neff Clay	9-11
S-3	950-1050	Sand	22-24

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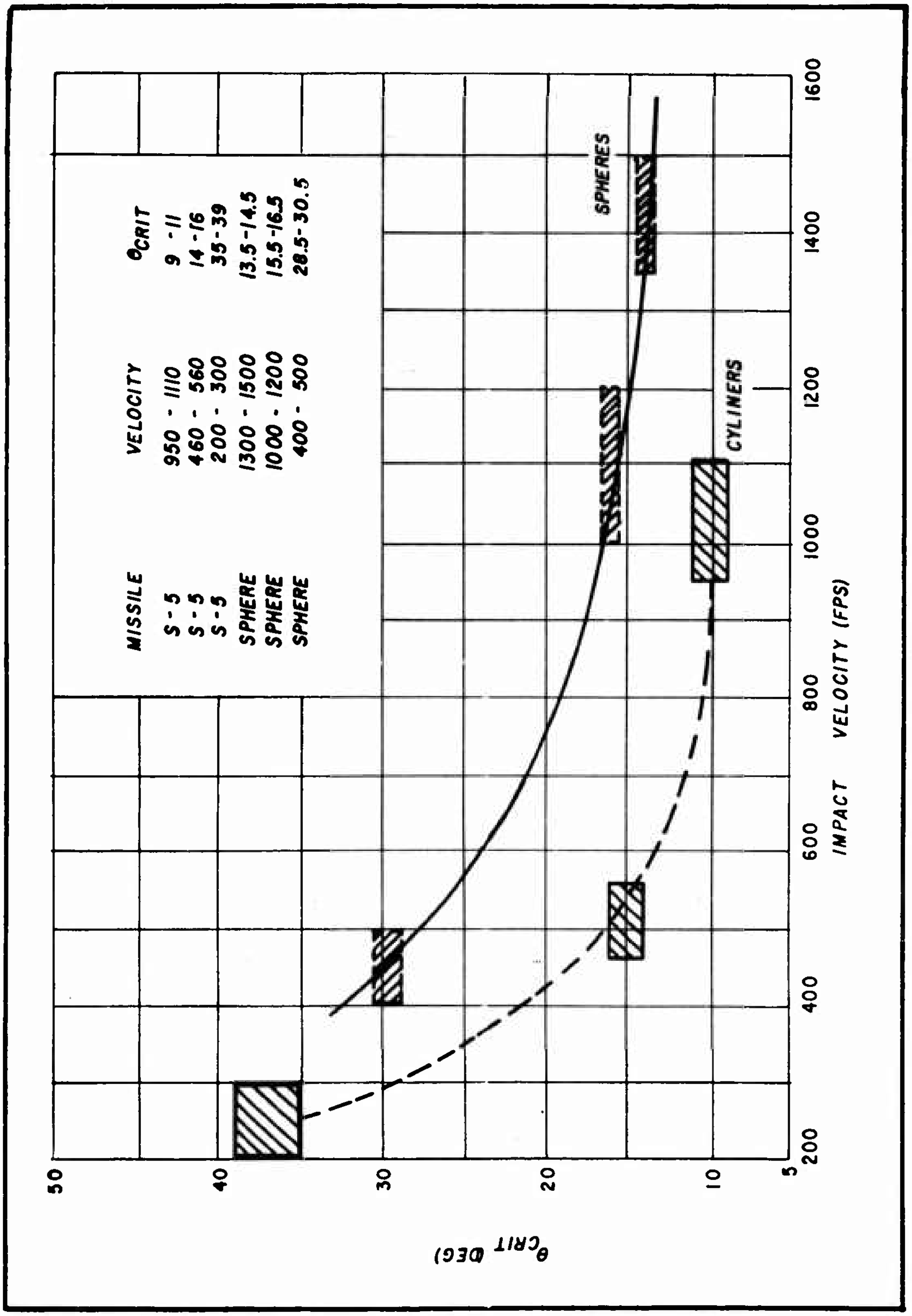

Fig. 10: Dependence of Critical Angle on Impact Angle for Clay Soils

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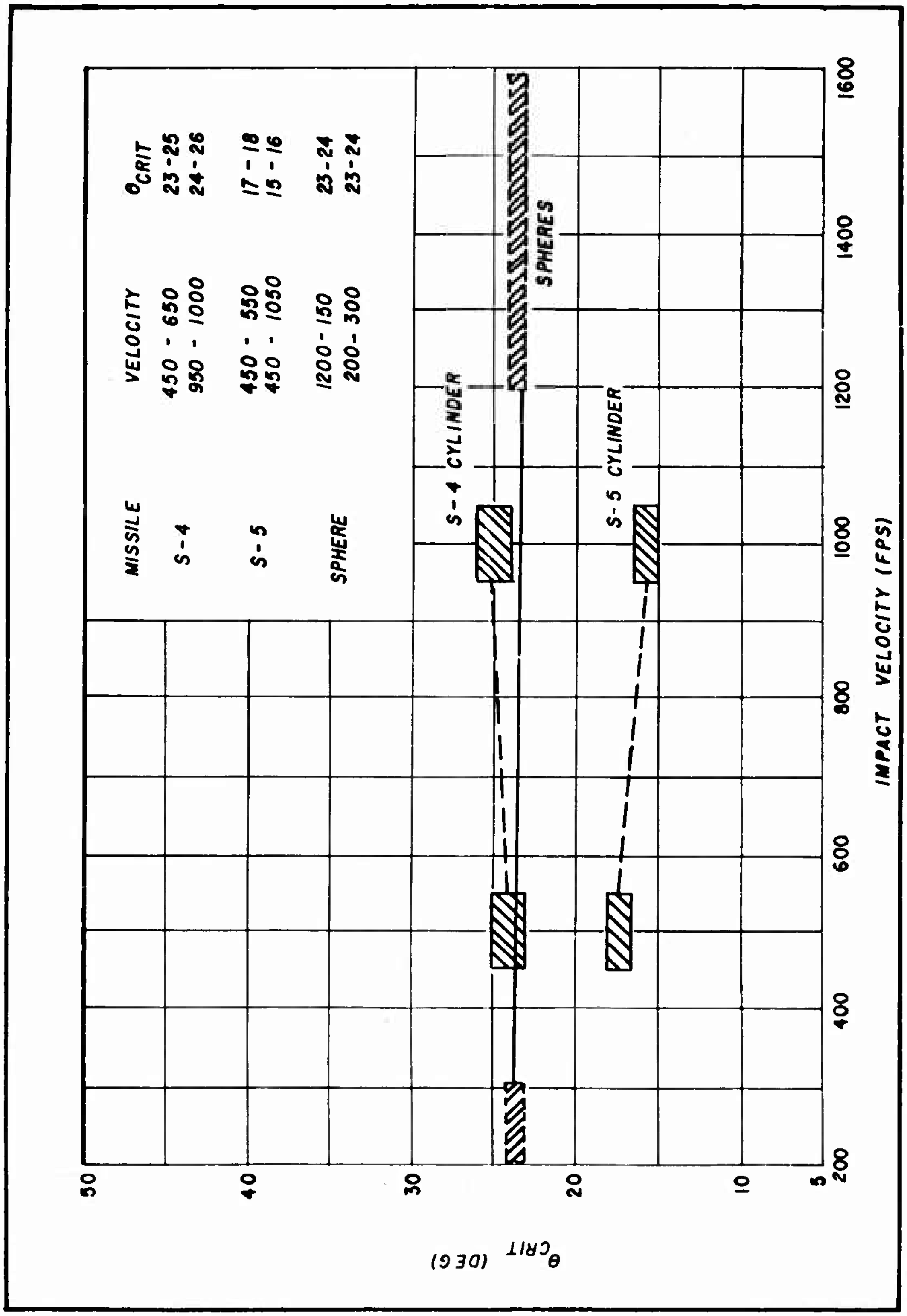

Fig. 11: Dependence of Critical Angle on Impact Angle for Sand Soils

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actual magnitudes of Θ_{crit}, but only to indicate a tendency.

In both the clay and sand soils, curves representing cylindrical missiles and spherical missiles are almost the same in general appearance. In sand, Θ_{crit} is practically independent of impact velocity for cylindrical and spherical missiles, while in clay Θ_{crit} decreases as the impact velocity increases.

Other tests conducted by Project Doan Brook with 1.367-in.-diameter missiles (Ref. 5) and with 14-in.-diameter bombs (Ref. 8) have also indicated that Θ_{crit} is virtually independent of impact velocity within the range of velocities tested in dry sand soils. There are no test data for larger diameter missiles in clay soils; as a result, it cannot be determined at this time whether the velocity dependence in clay soils holds for other diameter missiles. However, extrapolation of present data suggests that larger missiles should exhibit a similar tendency.

The fact that the S-6 conical-nosed missile had a slight higher Θ_{crit} than the S-5 blunt-nosed missile is not too significant in terms of delivery tactics. For an aircraft in level flight at 400 mph, a release altitude of about 390 ft would be required to obtain a 15-day impact angle; 500 ft, to obtain 17-deg; and 590, to obtain 18-deg. Thus, an increase in critical angle of 300 deg requires an increase of approximately 200 ft in altitude.

However, the apparently minor effect of nose shape on Θ_{crit} is important in terms of prototype design. The results of these tests have indicated that prototype aerial mine case might be designed with a conical nose rather than the proposed blunt nose. This would tend to increase the structural rigidity of the case without a significant sacrifice in anti-ricochet characteristics.

As indicated by Table 13, identical cylindrical missiles fired under the same conditions into sand have a higher Θ_{crit} than those fired into clay. Generally, this same trend was observed with the ricochet tests of spherical missiles in clay (Ref. 7). At low impact velocities, however, some of the spherical missiles had a higher Θ_{crit} in clay soils than in sand because of the velocity dependence of θ_{crit} in clay soils (see Table 10). The same result would probably be obtained when cylindrical missiles are fired into clay at very low velocities.

The results of the cylindrical missile ricochet tests in clay indicate that the clay type has only a slight effect on θ_{crit}. This is in sharp contrast to the results obtained with spherical missiles, where there was a spread of 11 to 30 deg in θ_{crit}. This great variation in θ_{crit} can be attributed to the difference in cohesive strengths of clay soils. The lower θ_{crit} was obtained in a soft, wet clay, while the higher θ_{crit} resulted from a hard, dry clay. Thus, range of 15 to 1 was obtained in the measurement of the cohesive strengths of the clays for the spherical shape tests, while the range was only 6 to 1 for the cylindrical missile tests. It is likely that larger variations of θ_{crit} would have resulted if clay soils having a greater range of properties had been employed.

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TABLE 14. TRIAXIAL-TEST DATA FOR CLAY SOILS

Clay Soils	Confining Pressure (psi)	Failure Stress (psi)	Bulk Density (lb/ft^3)	Moisture Content (% dry wt)
Mentor	0	12.4	125.8	22.8
	5	28.2	136.4	26.6
	5	35.3	126.3	27.4
	5	35.7	127.7	29.5
	5	25.6	127.9	24.5
	20	85.6	124.4	29.2
	20	64.2	119.8	28.0
	20	115.5	129.5	26.8
	20	88.0	122.2	25.1
	20	83.2	117.8	28.4
	20	96.4	118.4	26.5
Neff	5	95.1	131.3	14.9
	5	88.8	129.6	13.8
	5	101.7	127.8	17.4
	5	102.8	124.6	18.6
	5	108.9	125.7	13.4
	5	100.9	123.7	19.5
	5	102.0	122.4	18.6
	5	115.1	125.0	19.4
	5	105.6	122.1	18.0
	5	93.1	125.3	18.3
	5	103.8	126.3	14.4
	20	169.1	124.5	18.9
	20	151.6	127.6	15.4
	20	141.8	122.6	19.9
	20	161.7	130.4	15.3
	20	146.3	123.3	20.5
	20	126.6	121.1	22.1
	20	175.0	123.1	20.6
	20	150.3	119.3	20.0
	20	133.9	127.6	19.0
	20	144.3	124.7	18.4
	20	168.3	130.3	16.0
	20	160.8	127.4	16.9
	20	154.3	125.5	19.0
	20	154.3	123.8	17.2
	20	167.0	126.9	14.8
	20	123.9	125.4	15.5
	20	135.2	128.1	17.2
	20	127.1	129.2	16.4

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(Table 14, Cont.)

Clay Soils	Confining Pressure (psi)	Failure Stress (psi)	Bulk Density (lb/ft^3)	Moisture Content (% dry wt)
Auburn	5	38.3	120.0	21.4
	20	53.5	118.6	27.0
Chester	5	49.6	122.0	22.2
	5	54.6	127.8	21.5
	5	56.6	126.2	22.1
	20	102.4	125.3	21.5
	20	81.0	127.1	24.3
	20	100.0	128.7	22.2
Mean	-	-	126.2	22.3

TABLE 15. RICOCHET AND PENETRATION DATA

Missile	Soil	Impact Angle (deg)	Velocity Range (fps)	No. of Shots	Nonpenetration (%)	θ_{Crit} (deg)
S-5	Neff Clay	36 40 45	200-300	12 5 8	58 20 0	35-39
S-5	Neff Clay	8 10 12 14 16	460-555	9 9 11 8 9	100 89 91 63 33	14-15
S-5	Neff Clay	7.5 11 13 15	950-1110	12 11 6 0	55 42 26 0	9-11
S-4	Neff Clay	8 10 13 16	490-590	8 7 20 19	100 100 40 68	13-16
S-4	Neff Clay	8 10 12 14 16	910-1175	12 17 16 12 8	92 12 12 50 0	9-12
S-3	Neff Clay	8 12 14 16	510-600	6 17 5 8	100 71 40 0	12-14
S-3	Neff Clay	8 10 12 14	1110-1250	8 10 8 6	63 50 0 0	9-11
S-6	Neff Clay	15 16 17 18 19 20	425-525	8 10 9 8 10 9	100 70 56 63 30 0	17-19

(Table 15., Cont.)

Missile	Soil	Impact Angle (deg)	Velocity Range (fps)	No. of Shots	Nonpenetration (%)	θ_{crit} (deg)
S-5	Chester Clay	12 14	400-600	10 10	70 0	10-14
S-5	Auburn Clay	12 10	580-710	13 2	38 100	10-14
S-4	Mentor Clay	12 14 16	1000-1400	30 10 20	87 100 30	14-16
S-4	Mentor Clay	12 14 16	400-600	20 21 19	85 48 58	14-16

SECTION V

PENETRATION OF STEEL SPHERES IN CEMENTED SANDS

GENERAL

The tests described in this section deal with 0.356-in.-diameter steel spheres fired into cemented sand. The primary objectives of the experiments were:

1. To study the penetration properties of the steel spheres fired into this form of cohesive soils
2. To investigate the possibility of measuring the cohesive strength of a soil by means of penetration data
3. To test the validity of the Poncelet Force Law

Because of the difficulty in obtaining undisturbed samples suitable for laboratory tests from natural deposits of cemented sands, the tests were conducted with 16 soil blocks that were manufactured in the laboratory by methods that allowed control and measurement of cohesiveness. These cemented sand blocks were tested to obtain the following parameters: cohesion, angle of internal friction, bulk density, and moisture content.

Each target block was composed of dry sand, lime, Portland cement, and water. This mixture was thoroughly mixed in a cement mixer, packed in self-heating plaster-of-Paris molds, and allowed to heat and dry for about seven days. A block of fairly uniform moisture content, density, and strength properties was obtained. The sand was the same as that used in the tests described in Section IV of this report (see Fig. 10 for grain-size distribution curve).

The nominal dimensions of the blocks were 9 x 9 x 13 in., and they weighed between 75 and 85 lb. This relatively small size facilitated drying and handling. The desired variations in cohesive strength were obtained by varying the amount of lime and/or cement in the mixture. The angle of internal friction of the blocks was held fairly constant by employing the same type of sand in every block and by using a consistent method of packing the mixture in the molds. The compositions, drying times, and temperature of the blocks used are given in Table 16.

The physical properties of the cemented sand blocks are given in Table 17. Samples of each soil block were subjected to standard triaxial strength tests for the determination of cohesion and angle of internal friction (explained in Ref. 7). The tri-axial data for the 16 soil blocks are presented in Table 19 at the end of this section (beginning p. 67). The procedure for determining the other soil properties is also explained in Ref. 7.

Previous investigations by Project Doan Brook (Ref. 6 and 7) have indicated that the penetration-vs-velocity data for missiles into clay and sand soils conform to the Poncelet force law. The basic assumption of the Poncelet force law is that the resisting force, r, of the soil per unit-frontal-area of the missile is the sum of (1) a constant term, a, and (2) the product of a constant, b, and the square of the velocity, V, or $r = a + bV^2$ (a detailed explanation is given in Ref. 7, pp 13-15).

In these experiments, the length of penetration is defined as the distance from the point of impact on the target surface to the missile's center of gravity, plus a correction factor. This correction factor was equal to the length of a right circular cylinder having the same diameter as the sphere and a volume equal to that portion of the front hemisphere which is below the soil surface. This definition was adopted to provide a convenient means of comparing the data from this experiment with data from experiments in which missiles of different shapes were used.

RESULTS AND CONCLUSIONS

Penetration Properties

The experimental results of the penetration-vs-velocity tests for

TABLE 16. COMPOSITIONS, DRYING TIMES, AND TEMPERATURES OF CEMENTED SAND BLOCKS

Group No.	Composition (by Percent) of Total Weight				Drying Time (hr)	Drying Temperatures (deg F)
	Water	Lime	Sand	Cement		
1	19.8	9.1	71.1	0	116	116
2	18.4	10.2	71.4	0	90	122
3	18.7	8.3	73.0	0	140	128
4	15.2	8.7	76.1	0	93	156
5	15.2	8.8	76.0	0	192	113
6	15.5	8.7	75.8	0	192	127
7	18.4	10.2	71.4	0	420	70
8	15.9	8.6	75.5	0	118	194
9	16.6	7.5	74.9	1.0	141	119
10	16.1	7.5	75.3	1.1	128	108
11	16.1	7.5	75.3	1.1	117	110
12	14.7	5.5	76.5	3.3	286	109
13	13.8	5.3	74.5	6.4	192	113
14	14.5	5.5	76.7	3.3	202	110
15	14.3	5.5	76.9	3.3	168	110
16	14.3	5.5	76.9	3.3	168	106

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TABLE 17. SOIL PROPERTIES OF CEMENTED SAND BLOCKS

Group No.	Effective Cohesion (psi)	Angle of Internal Friction (deg)	Bulk Density (lb/ft^3)	Moisture Content (% total wt)	Poncelet Parameters a (psi)	Poncelet Parameters b ($lb\ sec^2/in.^4$)	No. of Shots
1	3.0	38.9	107	4.6	519	5.5×10^{-5}	40
2	2.0	34.0	105	7.6	344	4.6×10^{-5}	37
3	3.5	37.5	104	3.7	704	3.4×10^{-5}	18
4	1.0	43.5	103	0.2	1122	4.8×10^{-5}	22
5	8.0	36.0	105	0.1	1245	6.6×10^{-5}	19
6	4.0	39.0	107	3.0	994	4.9×10^{-5}	19
7	4.6	41.5	103	2.25	1112	4.7×10^{-5}	19
8	4.0	40.0	101	0	1180	7.8×10^{-5}	17
9	7.0	38.7	106	4.0	1460	3.5×10^{-5}	40
10	8.0	38.7	108	4.6	1045	3.9×10^{-5}	52
11	6.0	40.3	106	3.9	1760	4.1×10^{-5}	29
12	23.0	42.3	107	2.4	3170	7.6×10^{-5}	60
13	22.0	35.5	108	4.1	2980	7.1×10^{-5}	31
14	24.0	38.9	106	2.3	2980	7.1×10^{-5}	71
15	28.5	37.4	111	5.5	2420	6.4×10^{-5}	34
16	20.5	35.5	109	5.5	2210	6.3×10^{-5}	33
Sand	0	31.0	103	0	3.8	10.0×10^{-5}	48

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the cemented sand blocks and for loose sand are illustrated in Fig. 12A through 12Q, and summarized in Table 18. The effect of the cohesive strength of the cemented sand blocks is shown in Fig. 13 and 14. As indicated, the penetration length increased with increasing velocity and cohesion.

Measurement of Cohesion from Penetration Data

The Poncelet "a" and "b" values are compared with the soil properties of the cemented sand blocks in Table 17, and the cohesive strength of cemented sand blocks vs the Poncelet constant "a" is plotted in Fig.15. These data indicate that an approximately linear relationship exists between the Poncelet "a" value and cohesion. However, due to the deviation of individual points, the relationship has not been determined with sufficient accuracy to be used as a means of measuring the cohesion of natural cemented sands. Deviation of specific points from the curve representing the average value is probably caused by experimental errors in measuring the soil strength and determining the length of penetration.

Comparing these tests results with those for clay (Ref. 6) indicates that, in the cemented sand tests, the "a" value is more dependent on cohesion. This suggests that the magnitude of the "a" value is not entirely dependent on soil cohesion, but also on some other soil property or properties.

Validity of Poncelet Force Law

In Fig. 12A through 12Q, the penetration-vs-velocity curves are accompanied by the best-fit Poncelet curves for the cemented sand blocks tested. These graphs indicate that the Poncelet curves are a reasonable representation of the experimental data over the entire range of velocities studied.

There are large deviations of individual points from the Poncelet curves, especially at the higher impact velocities. This scatter was observable in all previous penetration tests and was assumed to be due to such factors as experimental error, missile instability, and lack of soil homogeneity. In the tests with cemented sand blocks, the penetration

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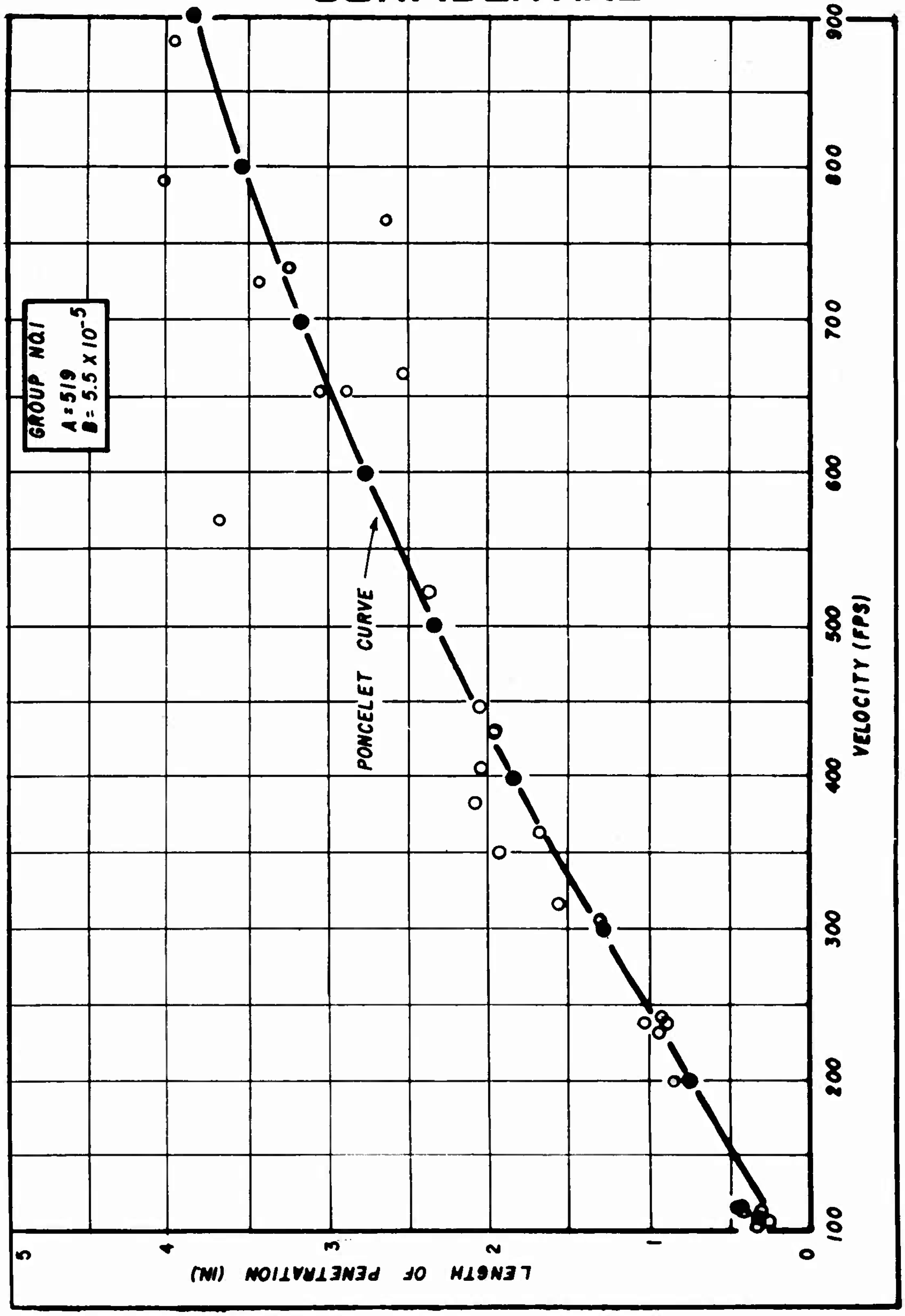

Fig. 12A: Penetration-vs-Velocity Data and Best-Fit Poncelet Curves for Cemented Sand Blocks

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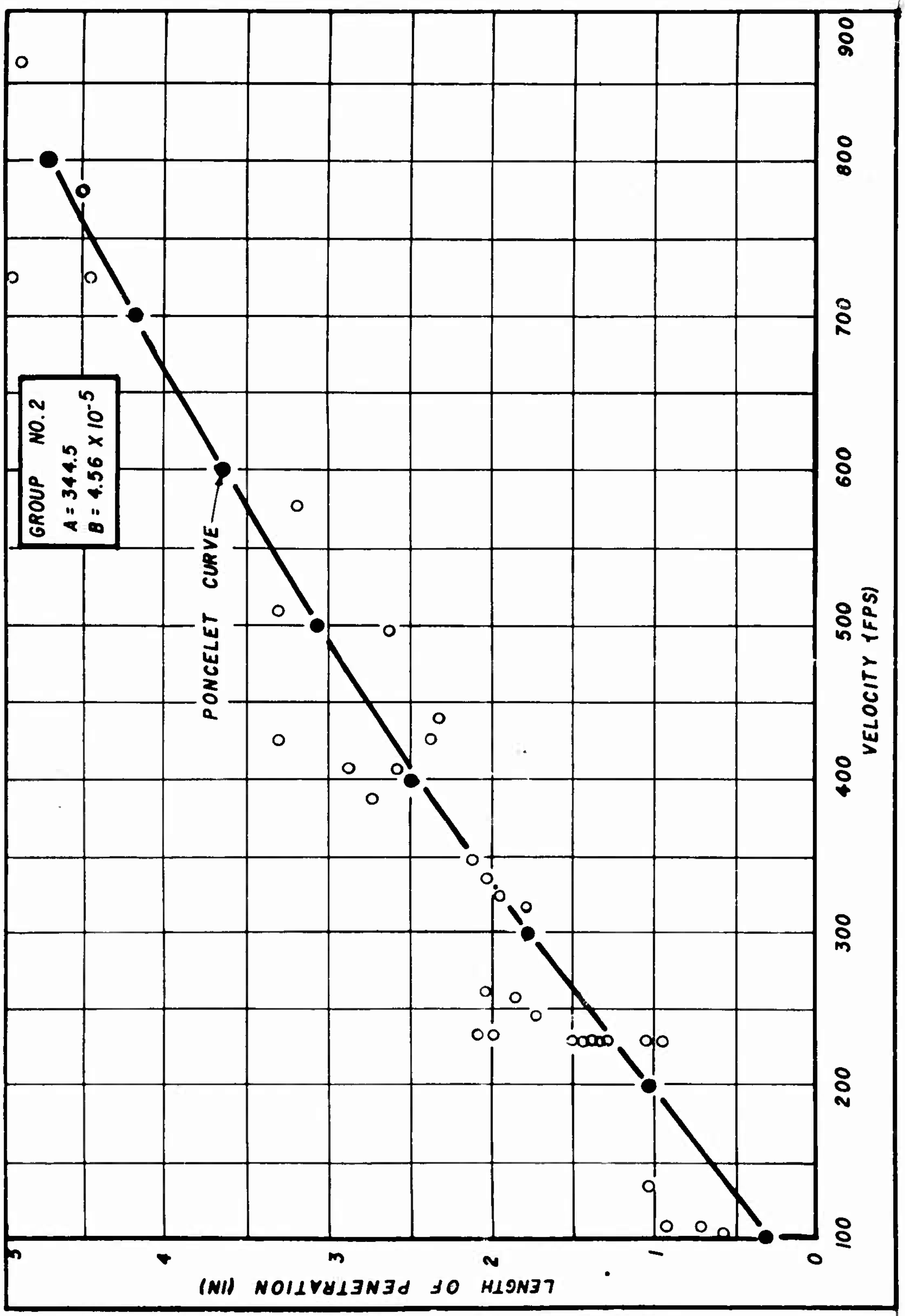

"Fig. 12B"

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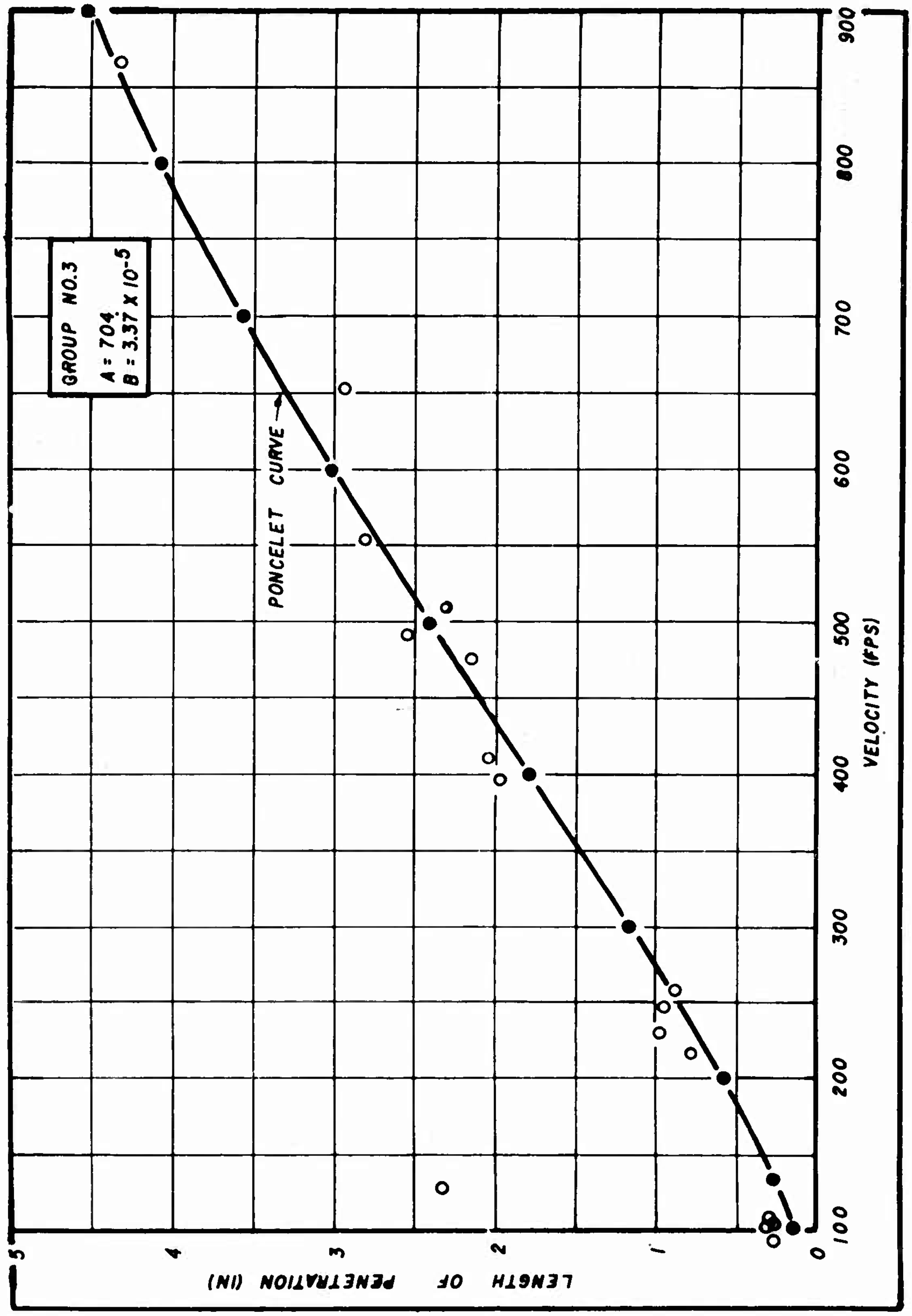

"Fig. 12C"

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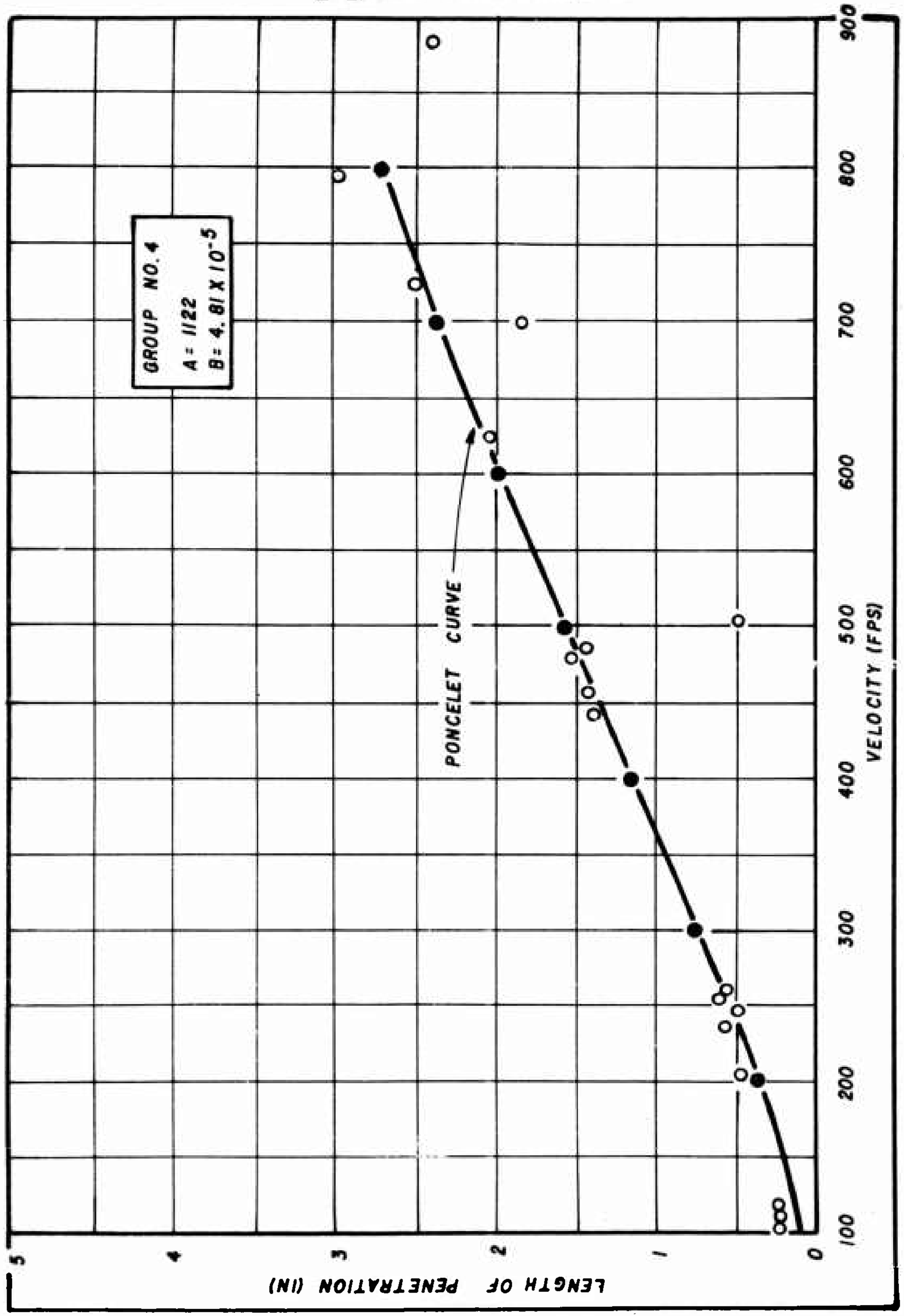

"Fig. 12D"

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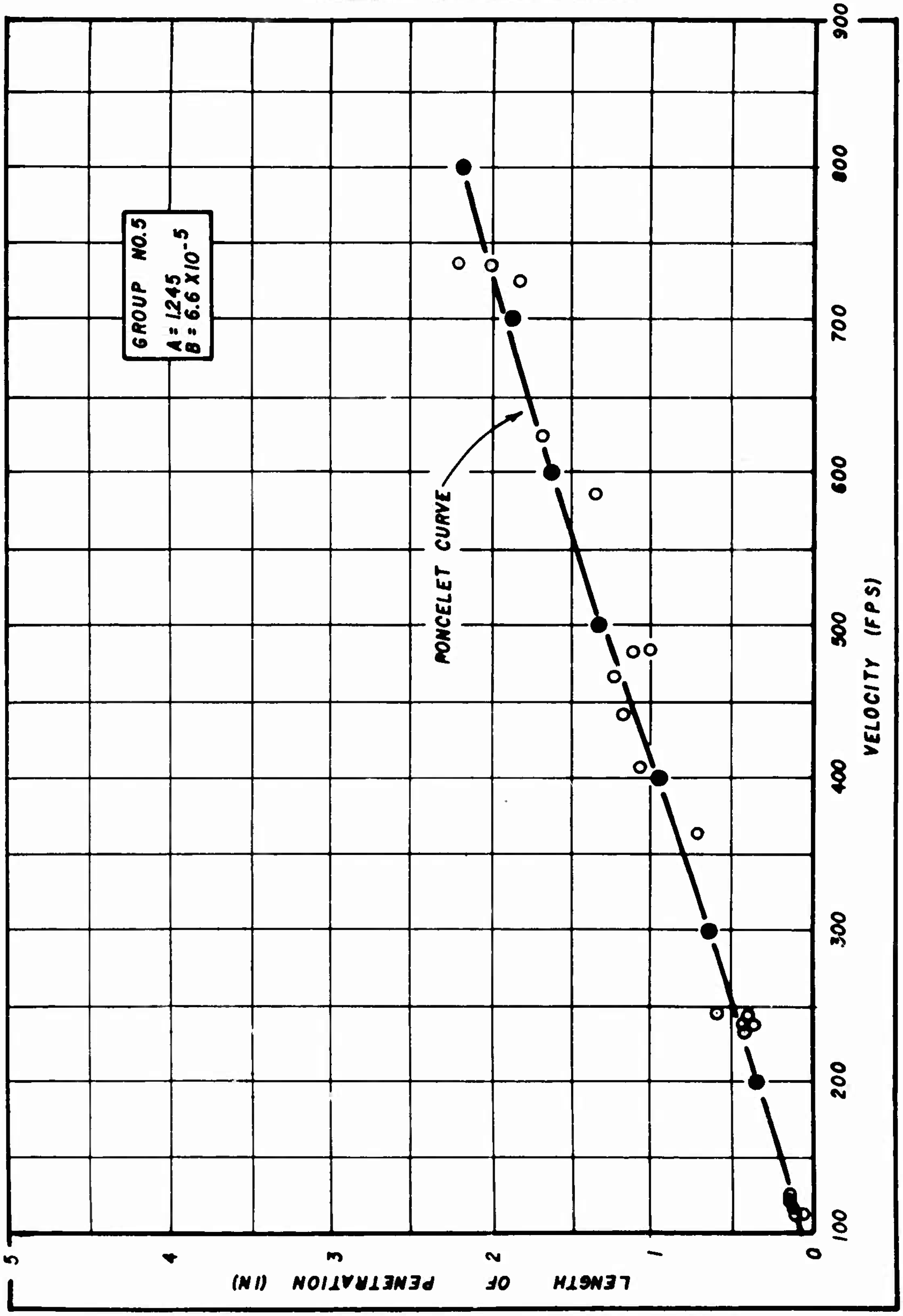
GROUP NO.5
A = 1245
B = 6.6 X 10^-5
PONCELET CURVE
VELOCITY (FPS)
100
200
300
400
500
600
700
800
900
LENGTH OF PENETRATION (IN)
0
1
2
3
4
5

"Fig. 12E"

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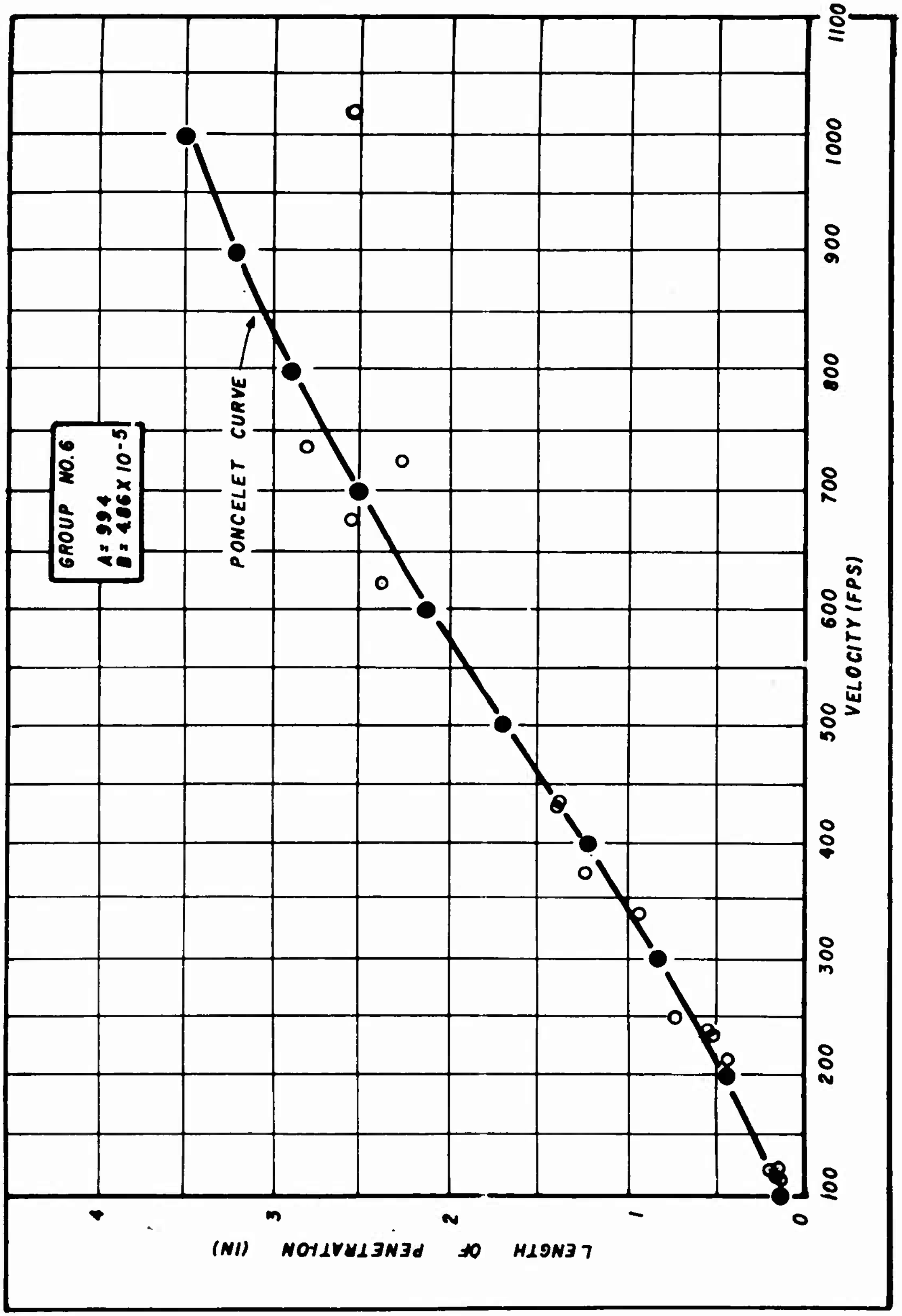

"Fig. 12F"

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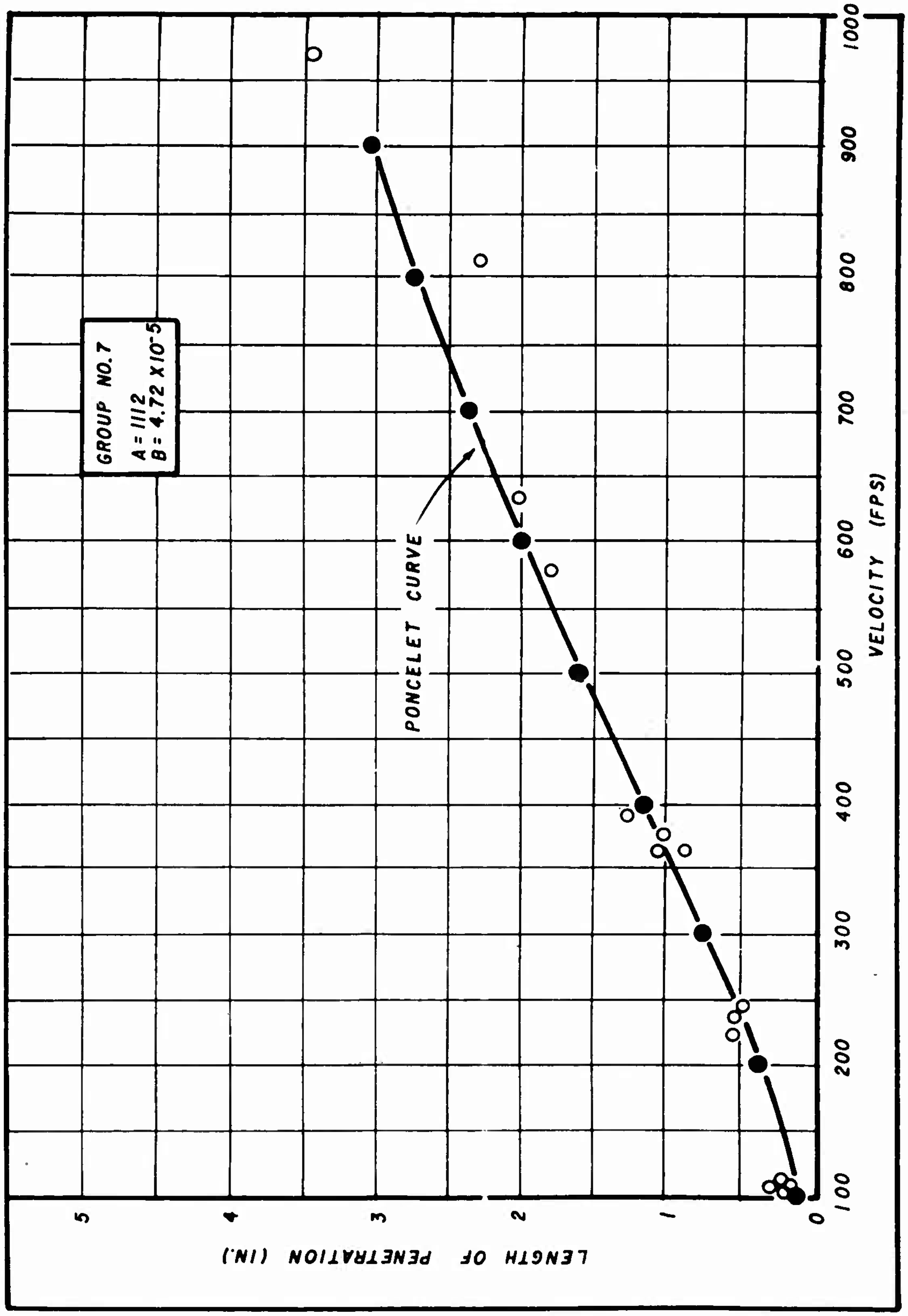

"Fig. 12G"

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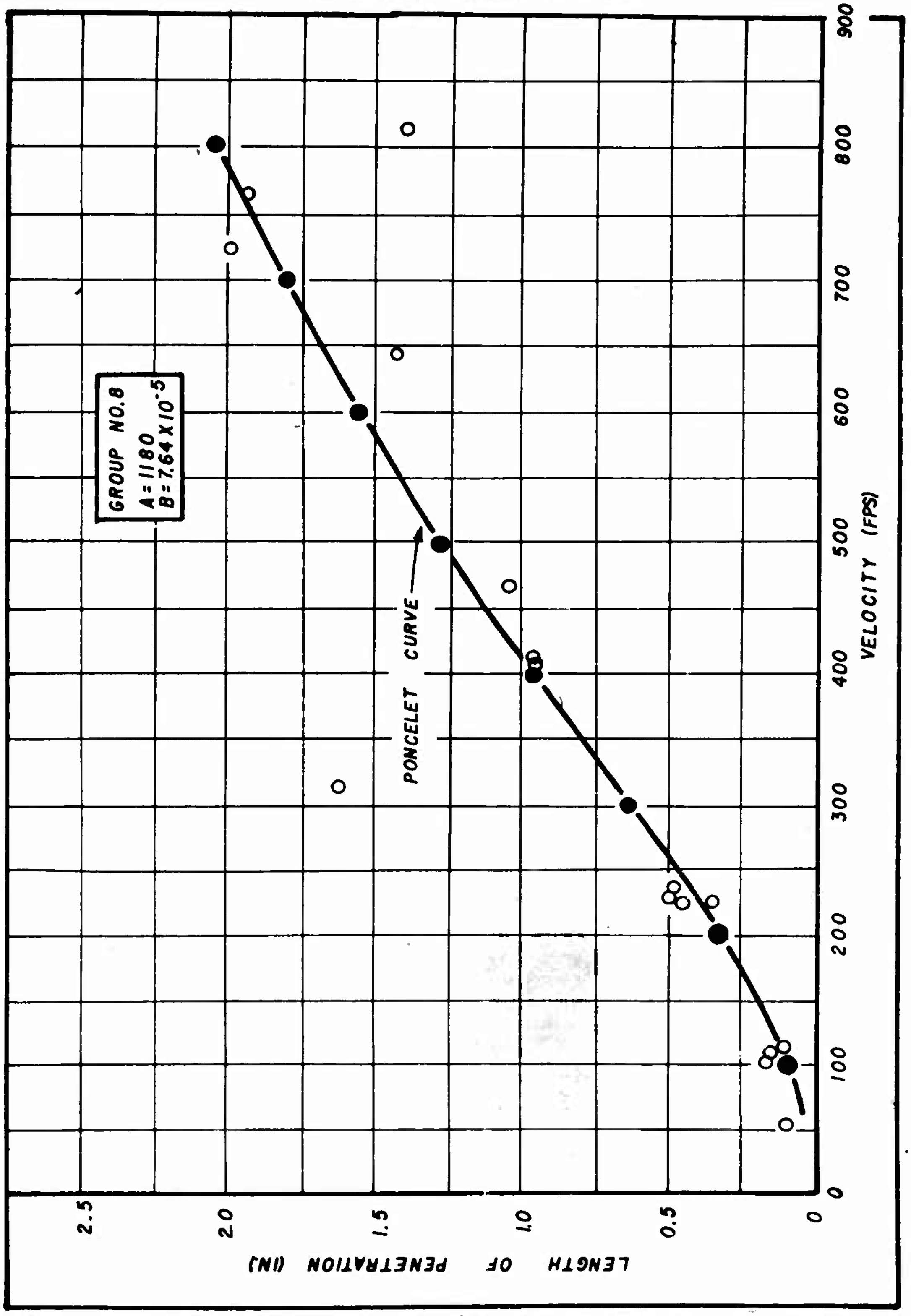

"Fig. 12H"

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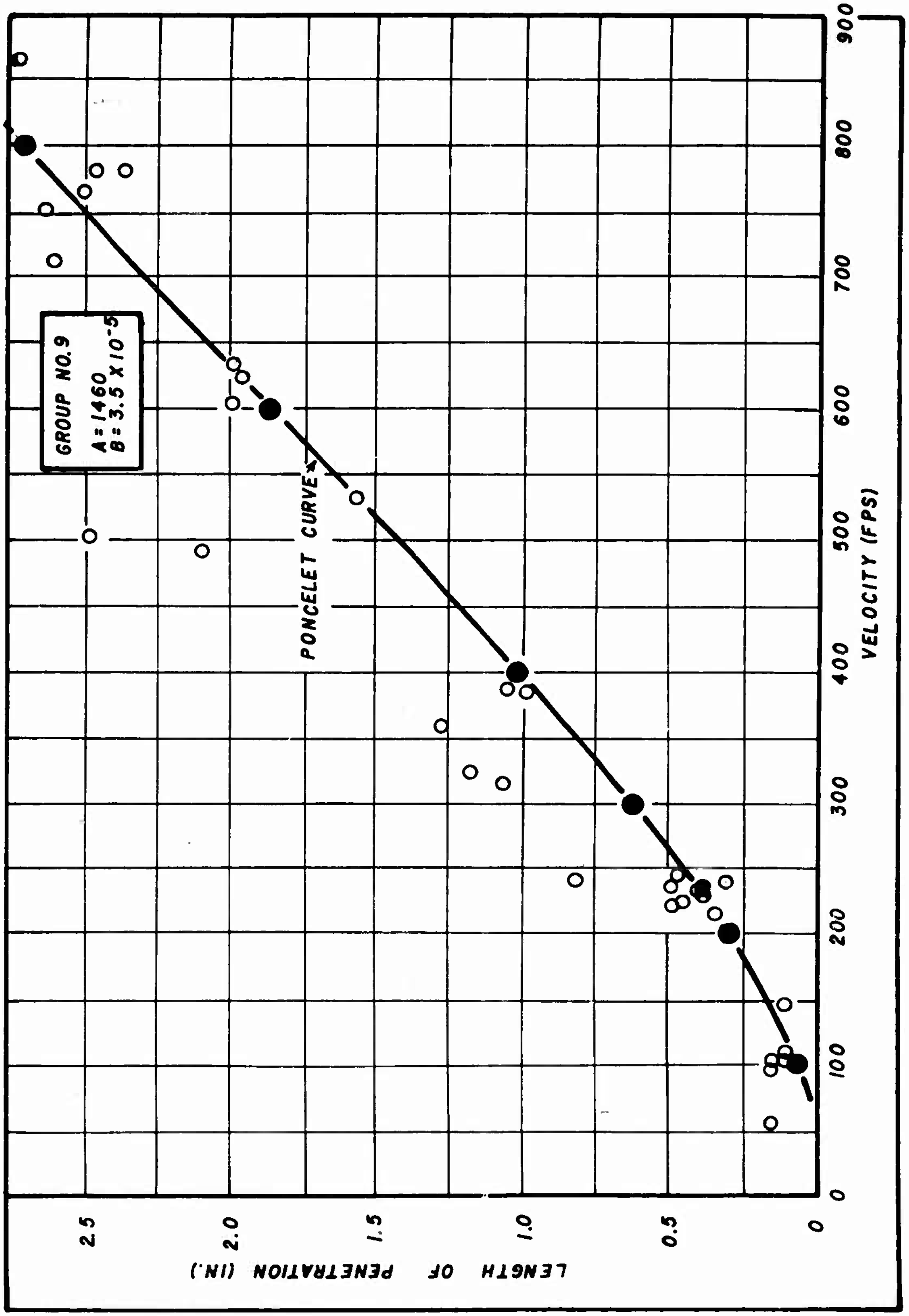

"Fig. 12I"

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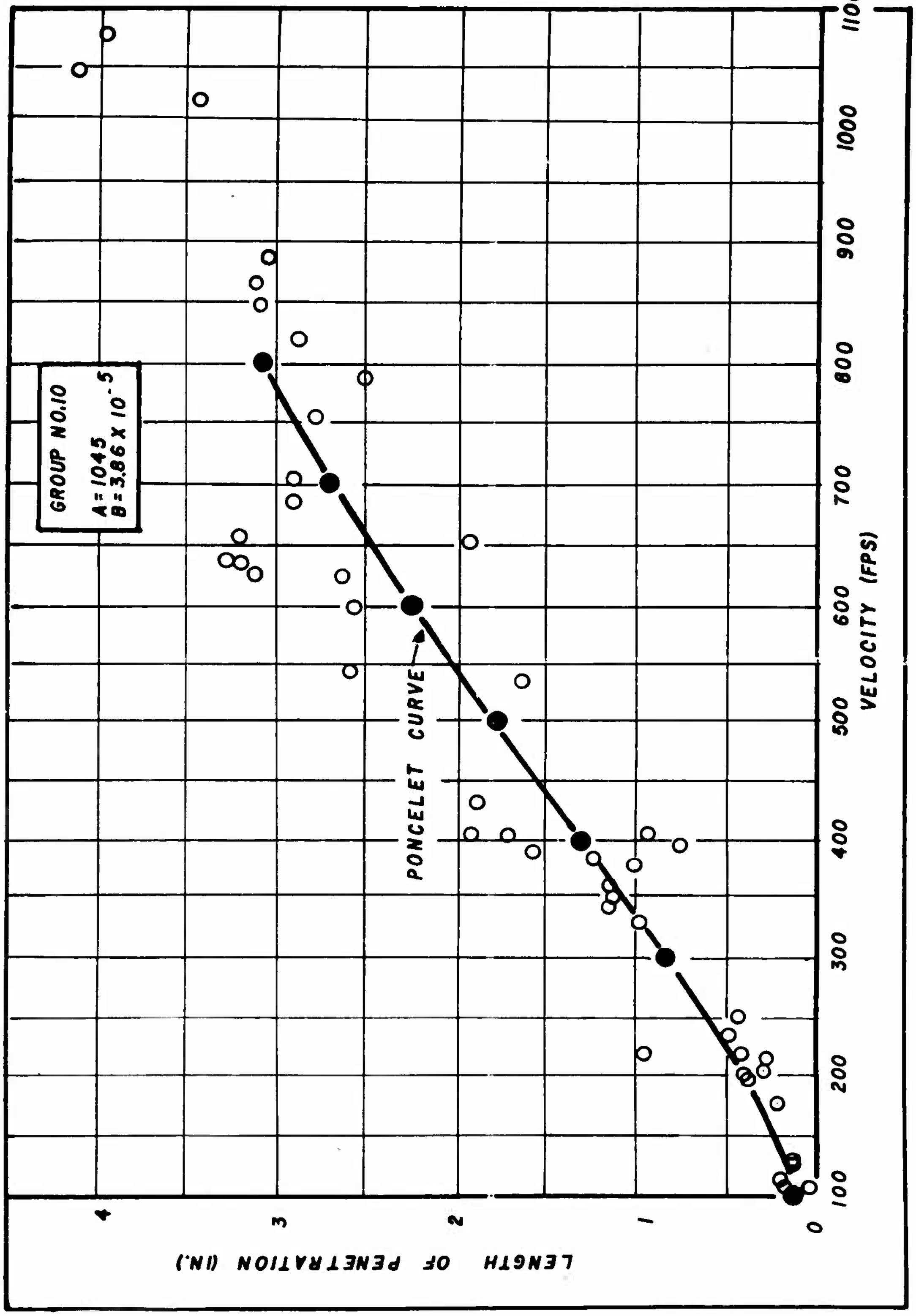

"Fig. 12J"

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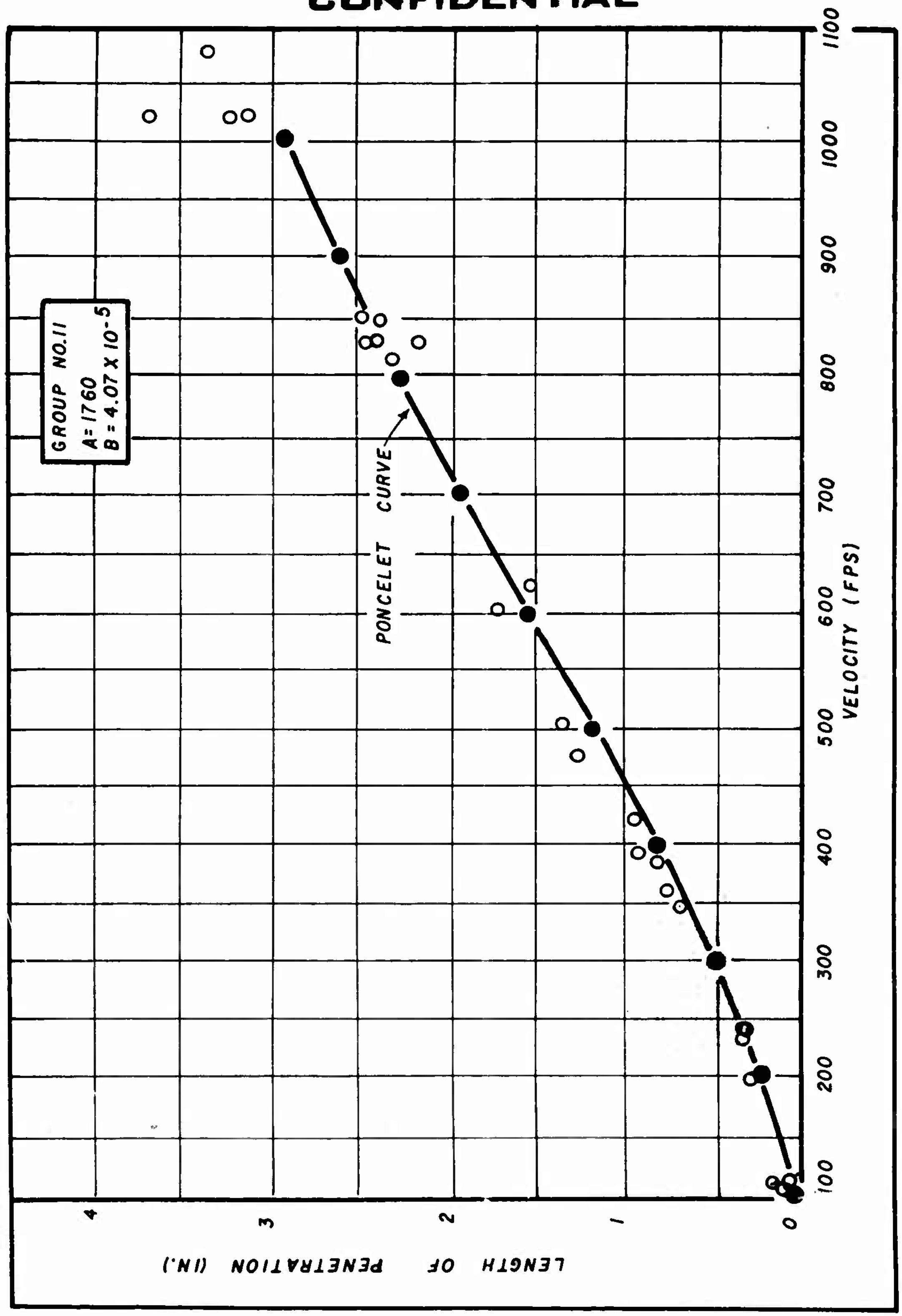

"Fig. 12K"

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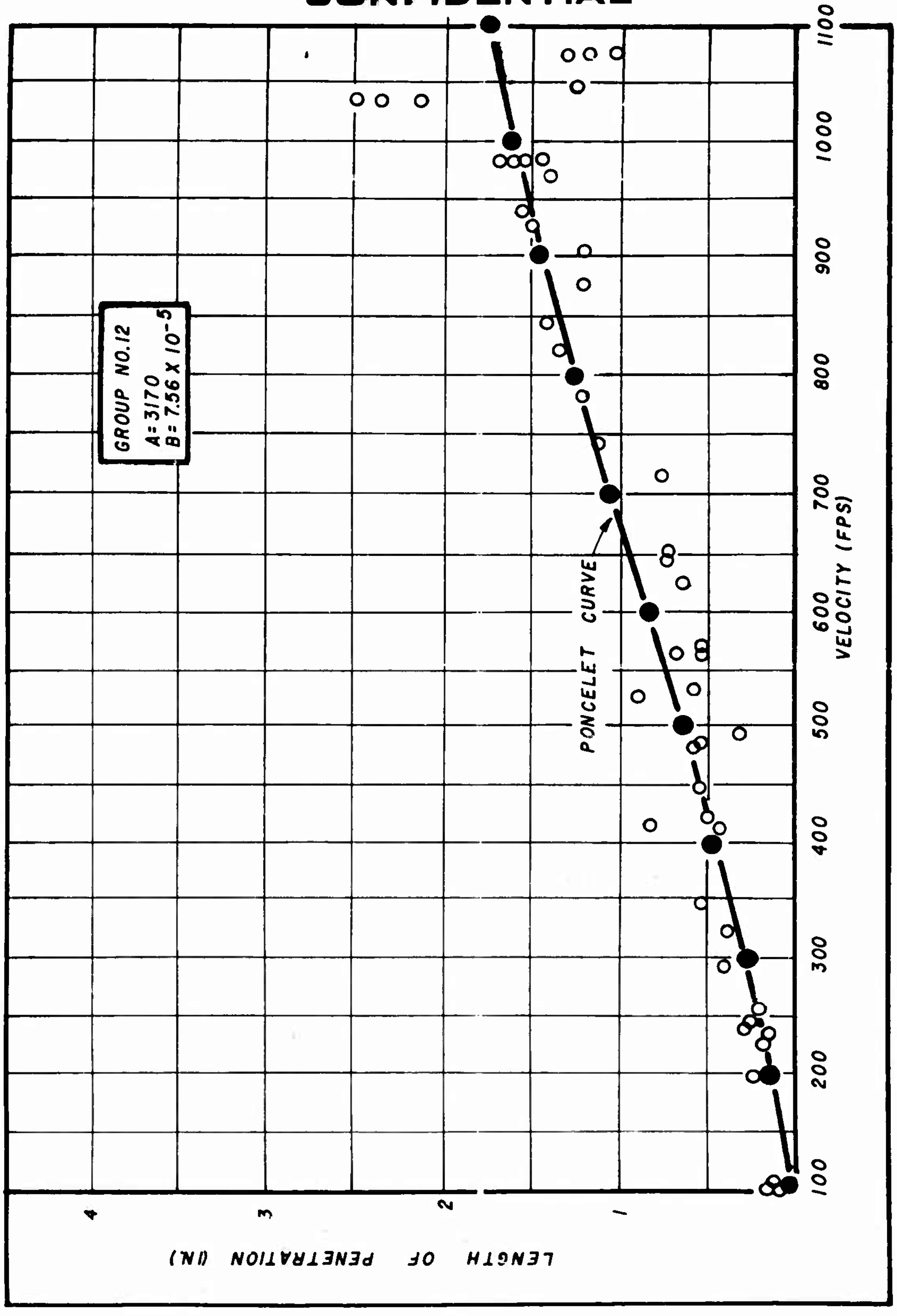

"Fig. 12"

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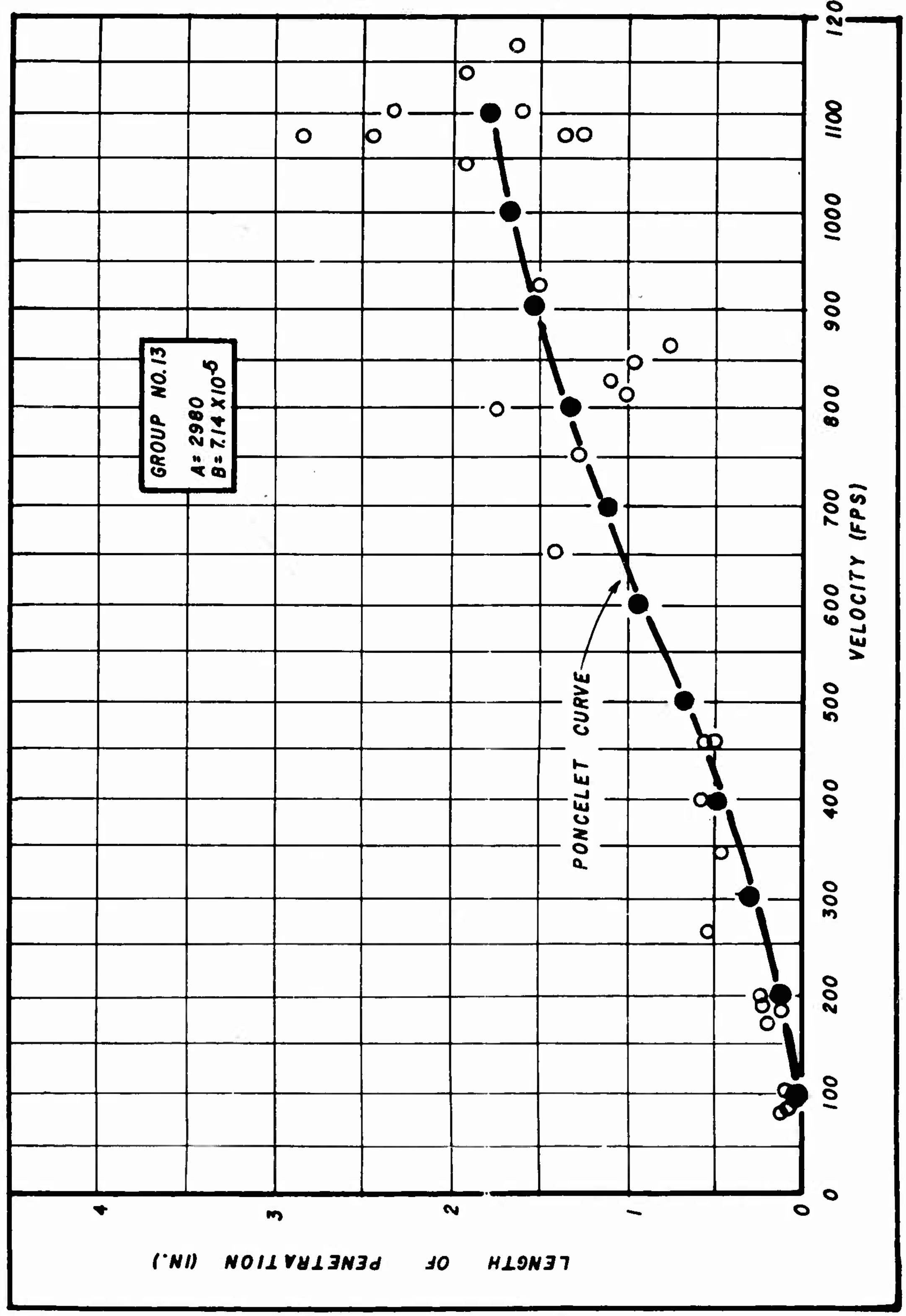

"Fig. 12M"

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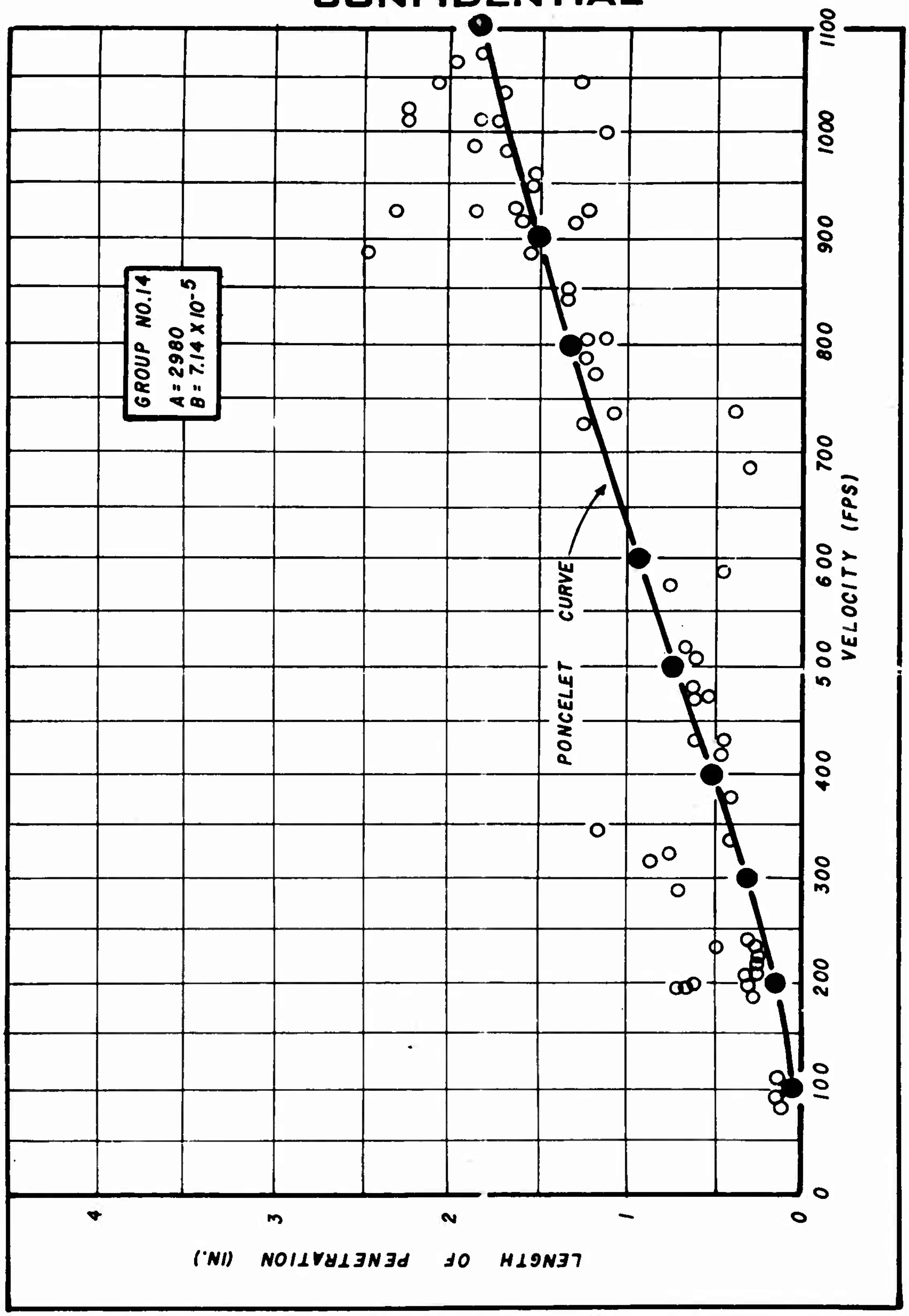

"FIG. 12N"

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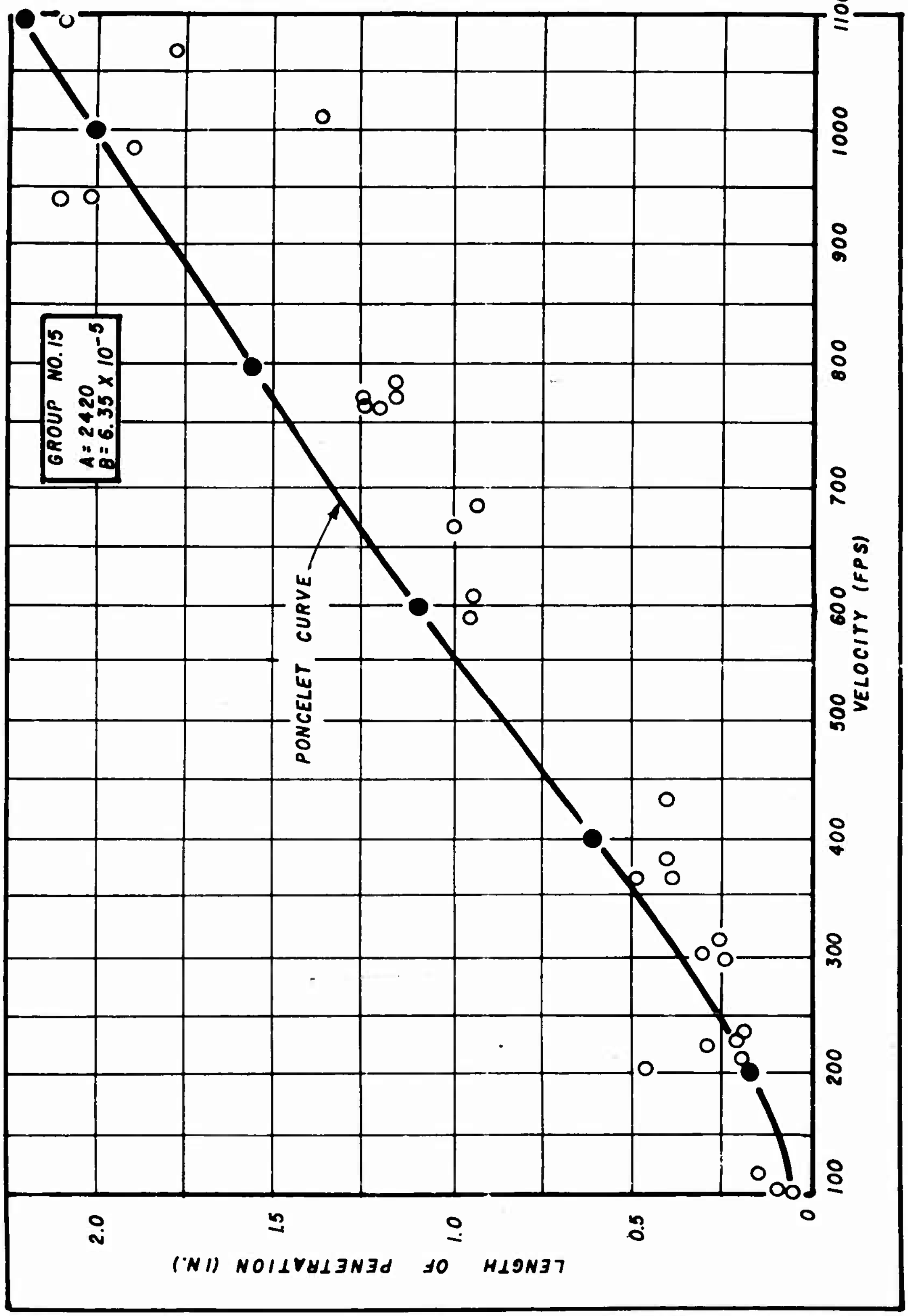

"Fig. 120"

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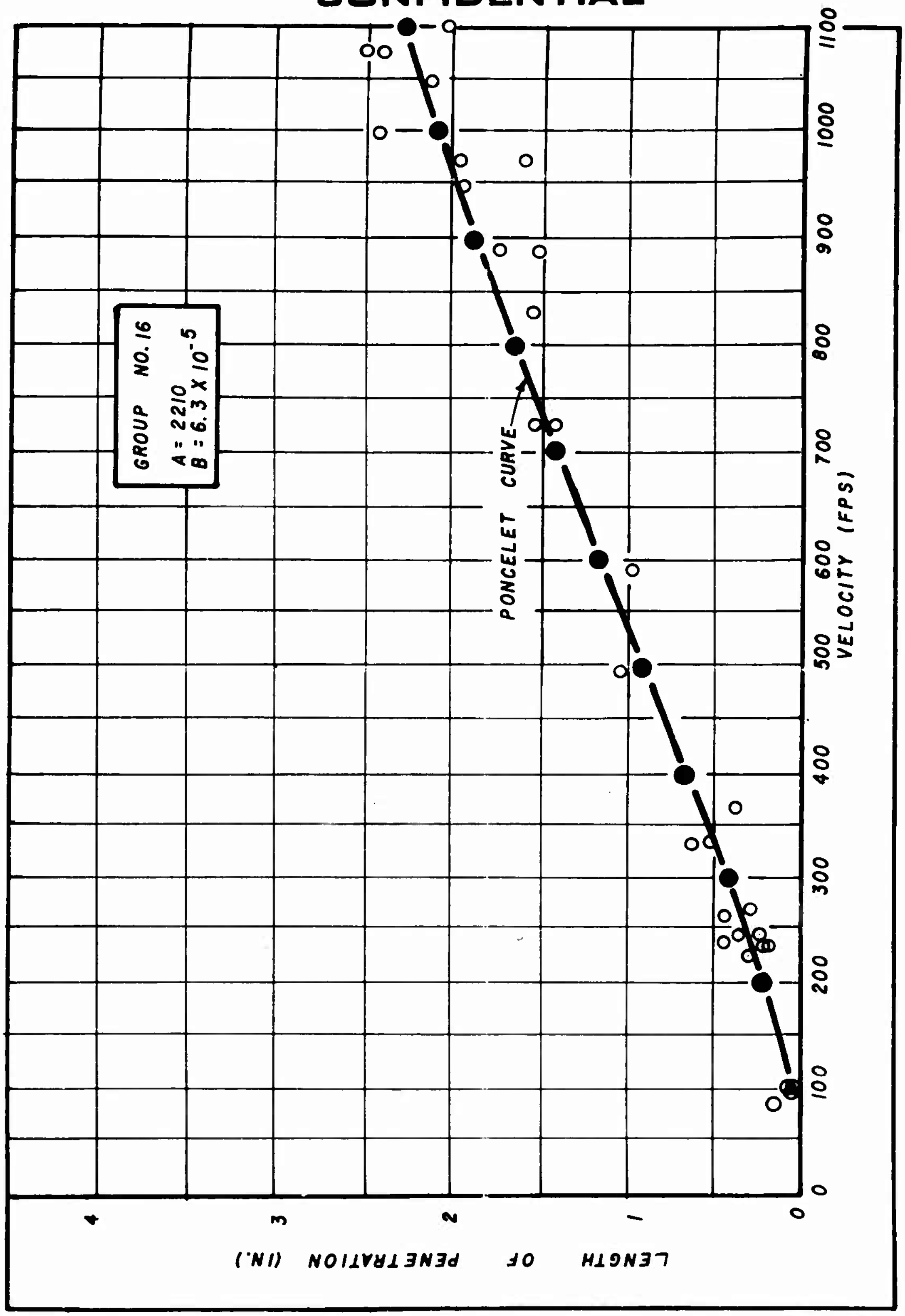

"Fig. 12P"

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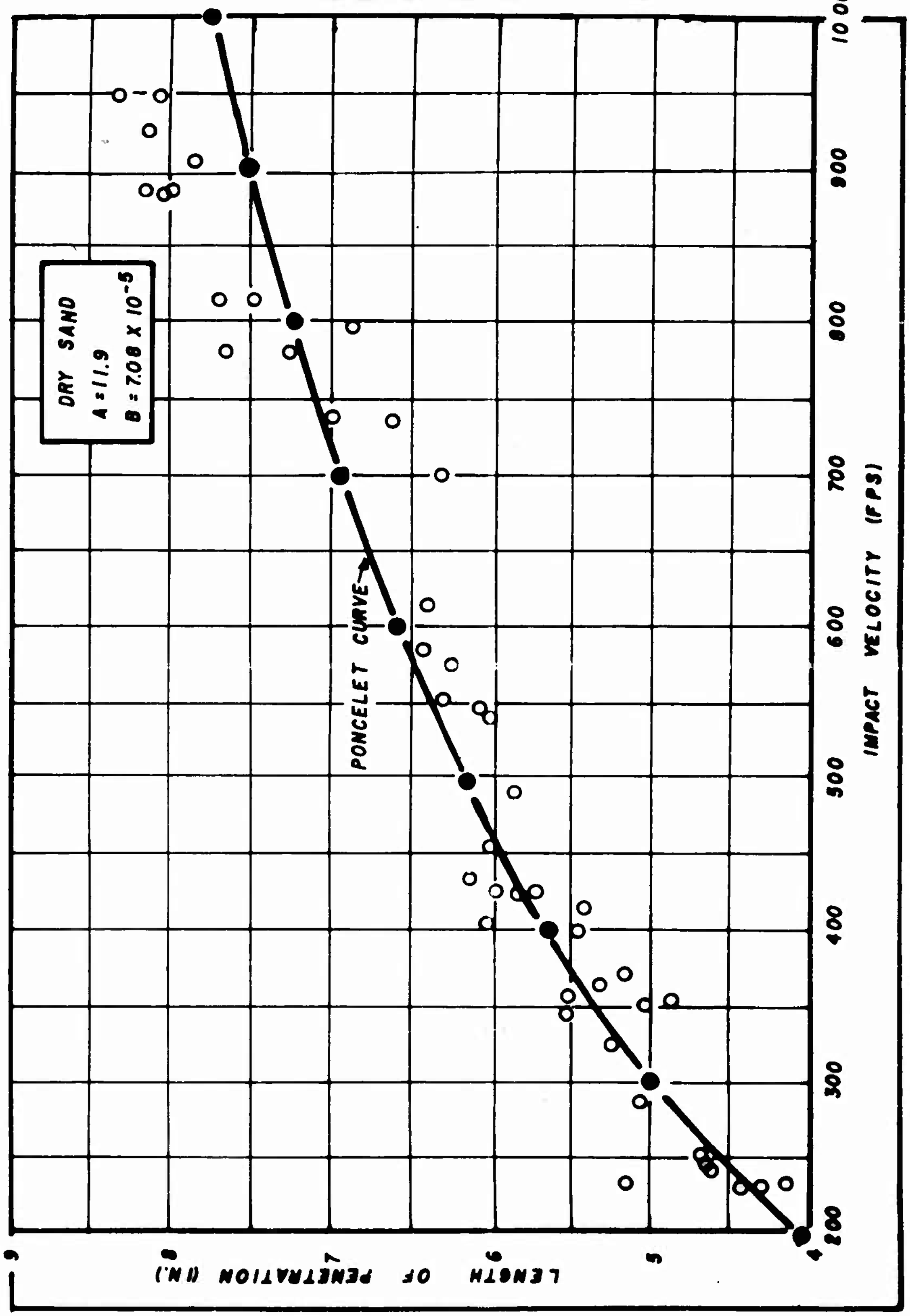

"Fig. 12Q"

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TABLE 18. PENETRATION OF SPHERES INTO CEMENTED SAND BLOCKS

Group No.	Cohesion (psi)	Average Length of Penetration (in.) at Velocities of:	
		200 fps	500 fps
1	3.0	0.7	2.3
2	2.0	1.0	3.0
3	4.0	0.28	2.4
4	3.5	0.35	1.6
5	1.0	0.32	1.3
6	8.0	0.38	1.8
7	4.0	0.34	1.6
8	4.6	0.33	1.25
9	7.0	0.30	1.45
10	8.0	0.20	1.8
11	6.0	0.24	1.2
12	23.0	0.15	0.7
13	22.0	0.15	0.7
14	24.0	0.15	0.7
15	28.5	0.18	0.7
16	20.5	0.18	0.83
Sand	0	4.0	6.1

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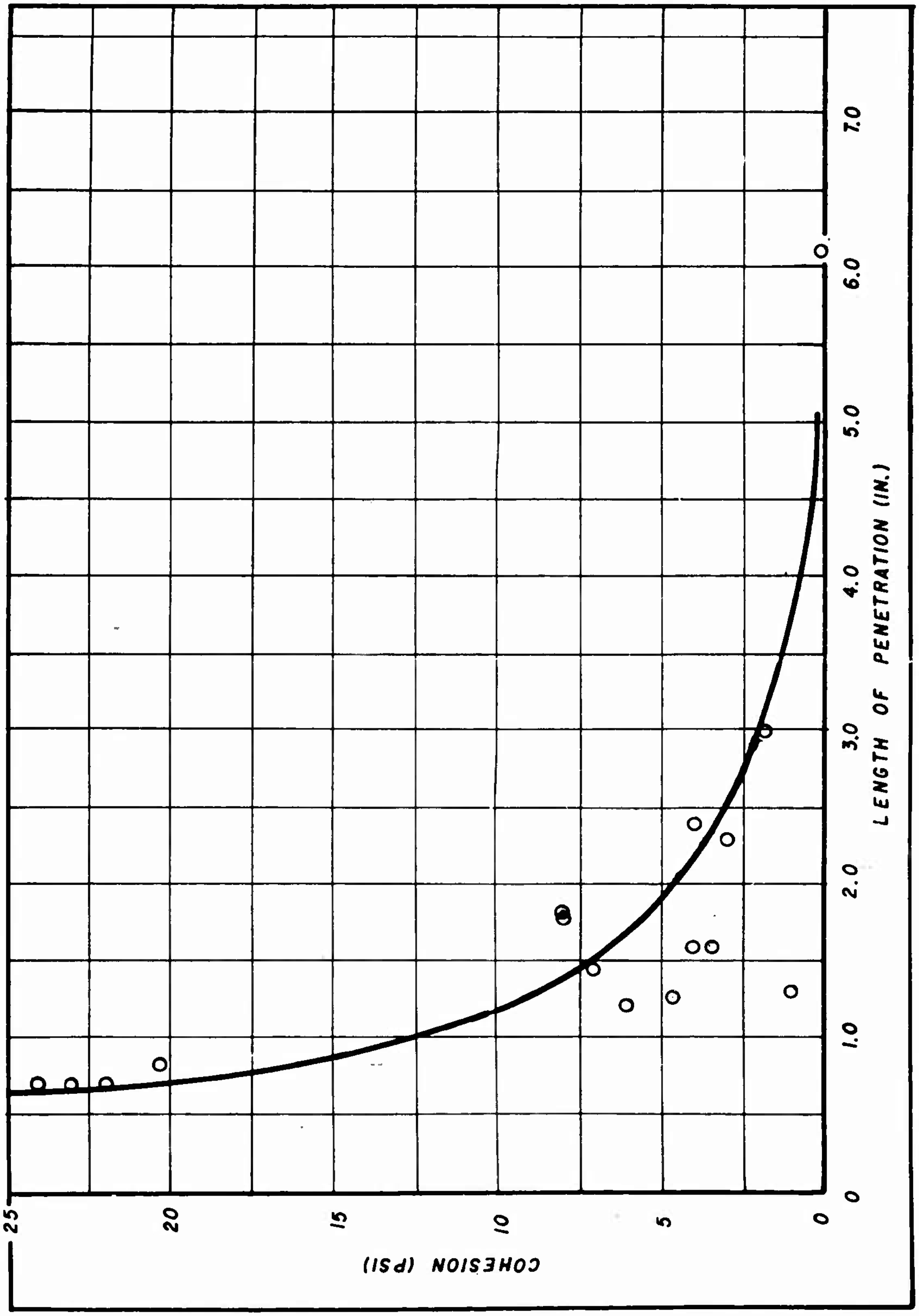

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Fig. 13: Effect of Cohesion on Length of Penetration

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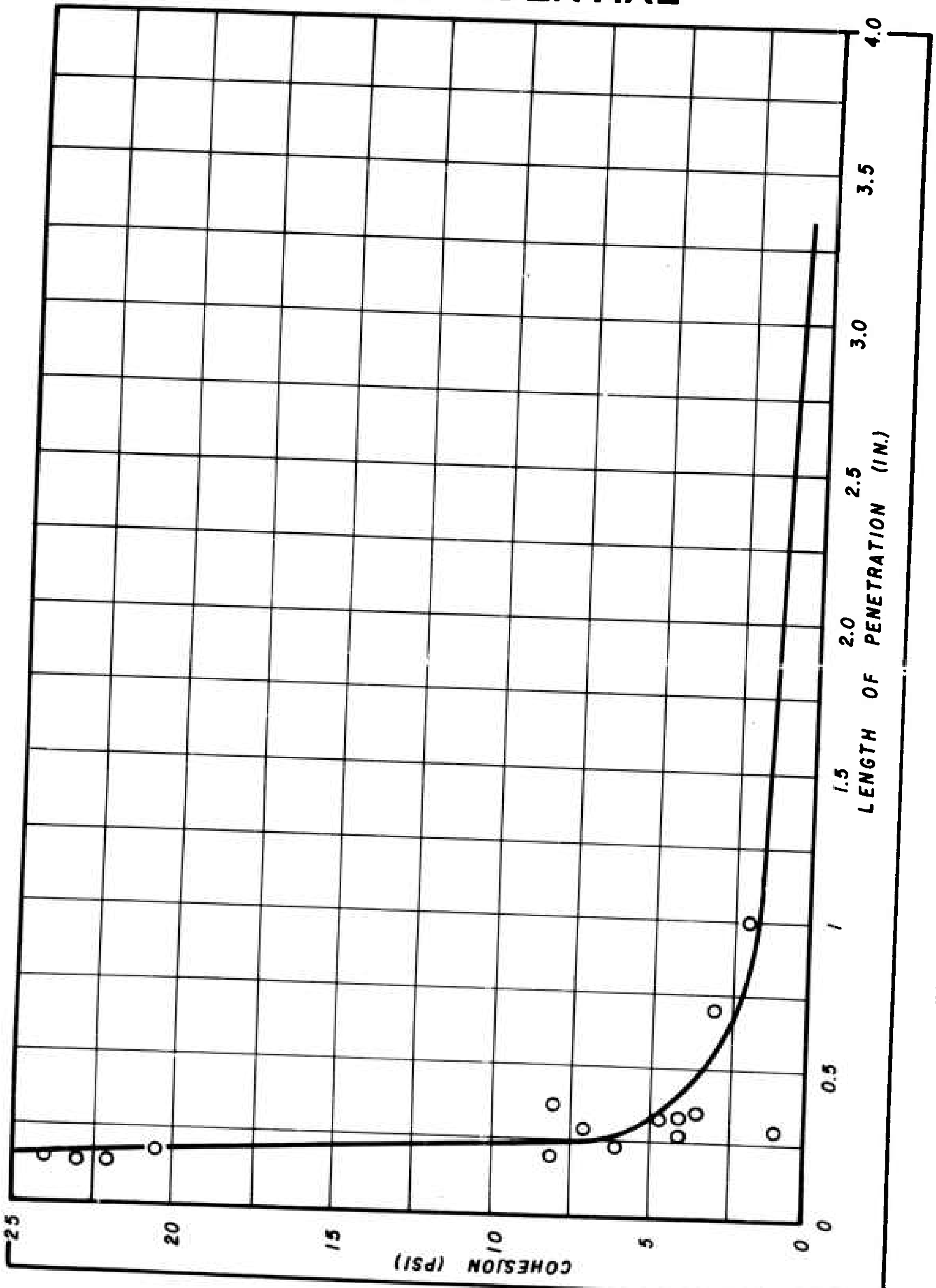

Fig. 14: Effect of Cohesion on Length of Penetration

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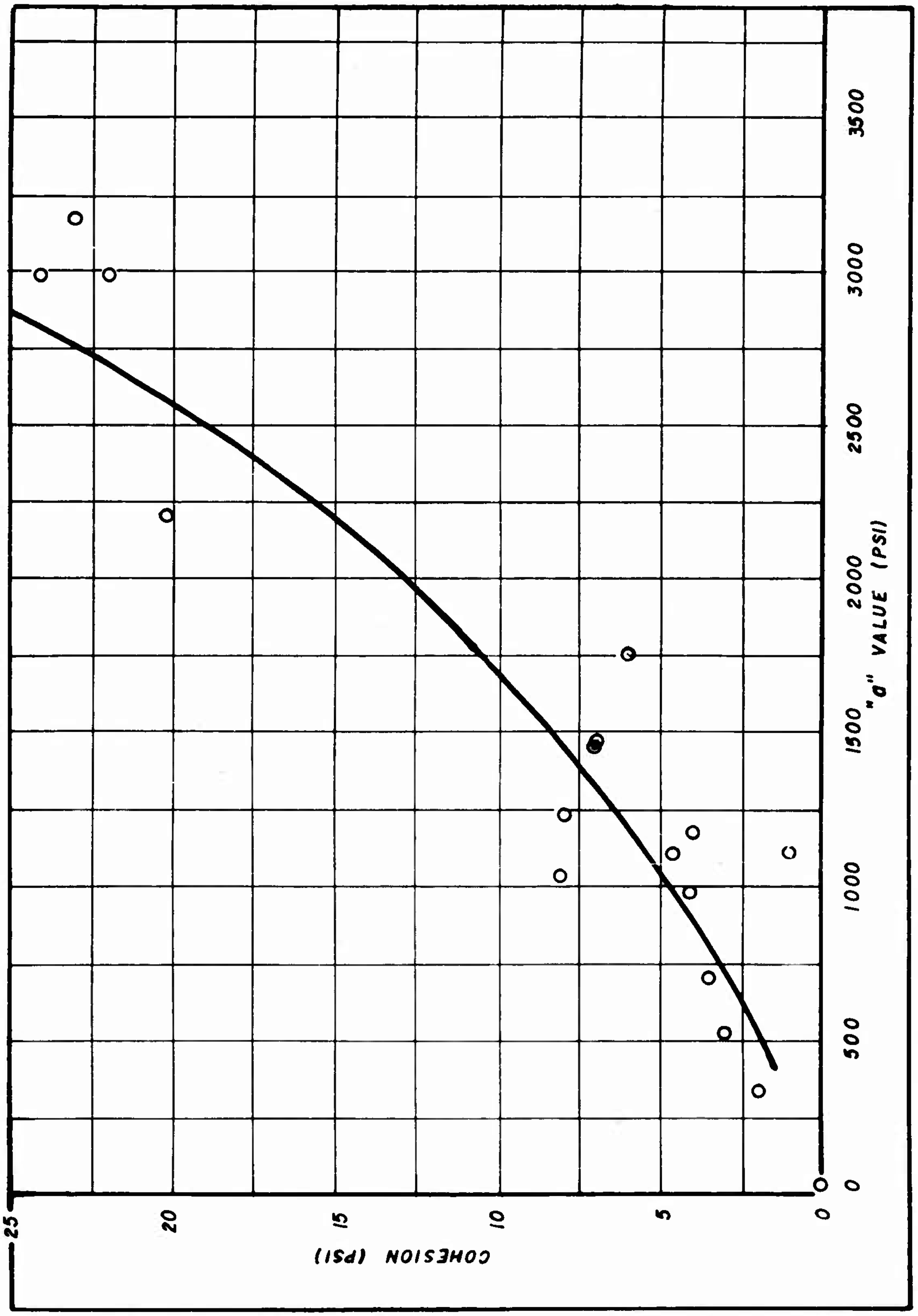

Fig. 15: Relationship between Cohesion and Poncelet "a" Value

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may have been affected by the fact that, because of the small size of the blocks, no sphere struck the target block more than four inches from a side. Minute cracks created by previous shots could also have affected penetration. However, the greatest source of error in determining the penetration-vs-velocity curve was the small number of shots that could be fired into each block. Sufficient data were usually available on the lower impact velocities, but usually only a few shots could be obtained at the higher velocities before a block was damaged beyond usability.

TABLE 19. TRI-AXIAL TEST DATA FOR CEMENTED SAND BLOCKS

Group No.	Confining Pressure (psi)	Failure Stress (psi)	Bulk Density (lb/ft^3)	Moisture Content (% dry wt)
1	0	10.4	109	4.0
	10	55.5	104	1.7
	0	18.2	106.2	5.71
	10	68.5	109	3.44
	0	23.4	108.5	3.16
	10	42.5	106	6.22
	5	29.0	108	6.17
	5	26.4	102	6.28
2	10	44.1	106	7.23
	10	39.2	103.5	-
	5	25.8	101.5	6.97
	5	22.9	107.5	8.74
3	5.2	36.4	105	-
	10.0	55.4	103.1	4.2
	5.2	33.1	101	3.0
	5.2	38.3	101.5	4.2
	10.0	55.4	105.8	3.3
4	9.4	53.3	101.5	0
	4.4	26.5	99.5	0.11
	9.4	56.5	101.0	0
	4.4	28.4	105.5	0.57
	9.4	53.2	109	0.12
5	5	58.9	108	0.41
	10	78.1	104.4	0
	5	57.0	110	0
	5	45.3	103.2	0
	10	65.0	105	0.43
	10	68.4	102.5	0
6	10	65.2	106.3	3.36
	0.6	20.1	107.3	2.76
	5	38.8	107	3.06
	5	37.4	107.2	3.16
	10	58.6	107.2	2.73

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(Table 19, Cont)

Group No.	Confining Pressure (psi)	Failure Stress (psi)	Bulk Density (lb/ft^3)	Moisture Content (% dry wt)
7	10	68.4	103	2.64
	5	44.6	102.2	2.90
	5	47.1	105	2.20
	10	73.3	103.5	1.27
8	10	63.9	99	0
	5.2	41.9	101	0
	10	62.8	100.5	0
	10	65.0	101.8	-
	5.2	40.2	99.5	0
9	5	63.4	105.0	4.5
	5	52.0	107.0	4.3
	10	76.5	109.5	3.6
	10	73.3	107.5	3.9
	20	125.5	107.5	4.2
	20	115.7	104.0	3.9
	5	42.0	103.9	4.2
	5	42.2	107	3.7
	20	109.3	108	3.6
	20	112.5	107.8	3.9
10	20	119	109.5	4.5
	10	89.5	109.5	5.2
	10	75.0	108	5.4
	20	114.1	110.5	5.7
	10	73.4	109.5	-
	5	49.1	108	-
	5	51.0	107	-
	20	112.5	104.6	-
	20	123.0	106.2	-
	20	112.5	109.5	-
11	5	114	4.0	-
	20	106	3.8	-
	10	73.3	106.8	3.6
	10	73.0	105	4.05
	20	119.6	107.2	4.1
12	20	205	108	1.62
	5	157.0	111	1.74
	5	118.8	105.5	2.10
	20	211.5	108	6.03

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(Table 19, Cont)

Group No.	Confining Pressure (psi)	Failure Stress (psi)	Bulk Density (lb/ft^3)	Moisture Content (% dry wt)
12	5	131.8	110	4.24
	20	212	102	0.51
	20	205	104.9	1.05
	20	186	107.2	2.08
	5	125.1	105.3	1.98
	5	92.5	107.9	2.87
13	20	153	108.2	4.22
	5	99.1	109.2	4.09
	20	160	105.0	3.72
	5	97.5	108.8	4.20
14	20	196	107.1	2.58
	20	179.5	106.6	1.46
	5	125.2	105.8	2.78
	10	146.8	106.0	2.50
	5	122.0	103.2	2.89
	20	176	107	1.68
	5	128	110	4.30
	5	115	106	2.42
15	5	125	110.5	4.60
	20	193	111.8	3.70
	20	196	112.5	7.90
	5	142	108.8	5.57
	20	202	111.0	5.71
16	5	99.3	110.5	3.75
	5	99.3	109.8	4.20
	5	86.3	108.4	5.37
	20	153.5	108.4	6.09
	20	153.5	106	7.95

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SECTION VI

PENETRATION OF MISSILES INTO SAND AT TACTICAL DELIVERY IMPACT ANGLES

GENERAL

The terminal ballistics studies described thus far in this report have been concerned with the determination of θ_{crit} or with the penetration of missiles in various soils at 90-deg impact angles. The primary purpose of the tests considered in this section was to measure the penetration characteristics of missiles when fired into sand at those acute impact angles which are lower than 90 deg but higher than θ_{crit} -- specifically, at impact angles ranging from 20 to 40 deg. The significance of these studies lies in the fact that this 20- to 40-deg impact angle range corresponds closely with the expected delivery tactics of the Project Doan Brook aerial mine.

Two secondary objectives of these tests were:

1. To determine whether an empirical equation -- previously derived to predict penetrations at 90-deg impact angles (Ref. 6) -- could be applied to penetrations at the 20- to 40-deg range.
2. To determine whether the penetrations from the model studies could be used to predict similar results with full-size models.

The tests were conducted by firing models of 1.367-in.-diameter missiles into Portage 40-60 sand. Three blunt-nosed missiles were used -- the C-3, the C-6, and the A-6. As indicated previously, the C-3 anti-ricochet missile was designed by Project Doan Brook (see Fig. 4). The C-6 is a modification of the C-3 (see Fig. 7, Ref. 5). The A-6 represents a modification of the GP 500-lb bomb shape (see Fig. 5, Ref. 5).

RESULTS

Method

The effect of impact velocity on the length of penetration is discussed in terms of an equation derived from the Poncelet Force Law. Previously, derivations were made for a 90-deg impact angle where, in the case of a blunt-nosed missile, the entire cross-sectional area was immediately in contact with the soil (Ref. 6, pp. 13-16). At acute angles, the area of contact with the soil is a function of the length of penetration before the face is entirely in contact with the sand. Under these impact conditions, the length of penetration, S, can be expressed as

$$S = \frac{m}{bA} \ln\left(\frac{b}{a} V_o\right) + \frac{r}{\tan \Theta},$$

where:

S = total length of penetration,
m = mass of missile,
A = cross-sectional area of missile,
V_o = initial impact velocity,
r = radius of missile,
Θ = impact angle, and
a and b = constants from Poncelet Force Law.

This equation is derived at the end of this section (beginning p. 84).

The test data were analyzed in terms of (1) length of penetration vs impact angle, (2) depth of penetration vs impact angle, (3) length of penetration vs impact velocity, and (4) missile stability. The length of penetration, S, was measured as the distance from the point of impact to the missile's center of gravity (see Fig. 16). The depth of penetration, Z, is defined as the vertical distance from the original sand surface to the missile's center of gravity (see Fig. 16). All the penetration data are summarized in Table 24 at the end of this section (beginning p. 88).

A quantitative comparison of the relative stability of the various

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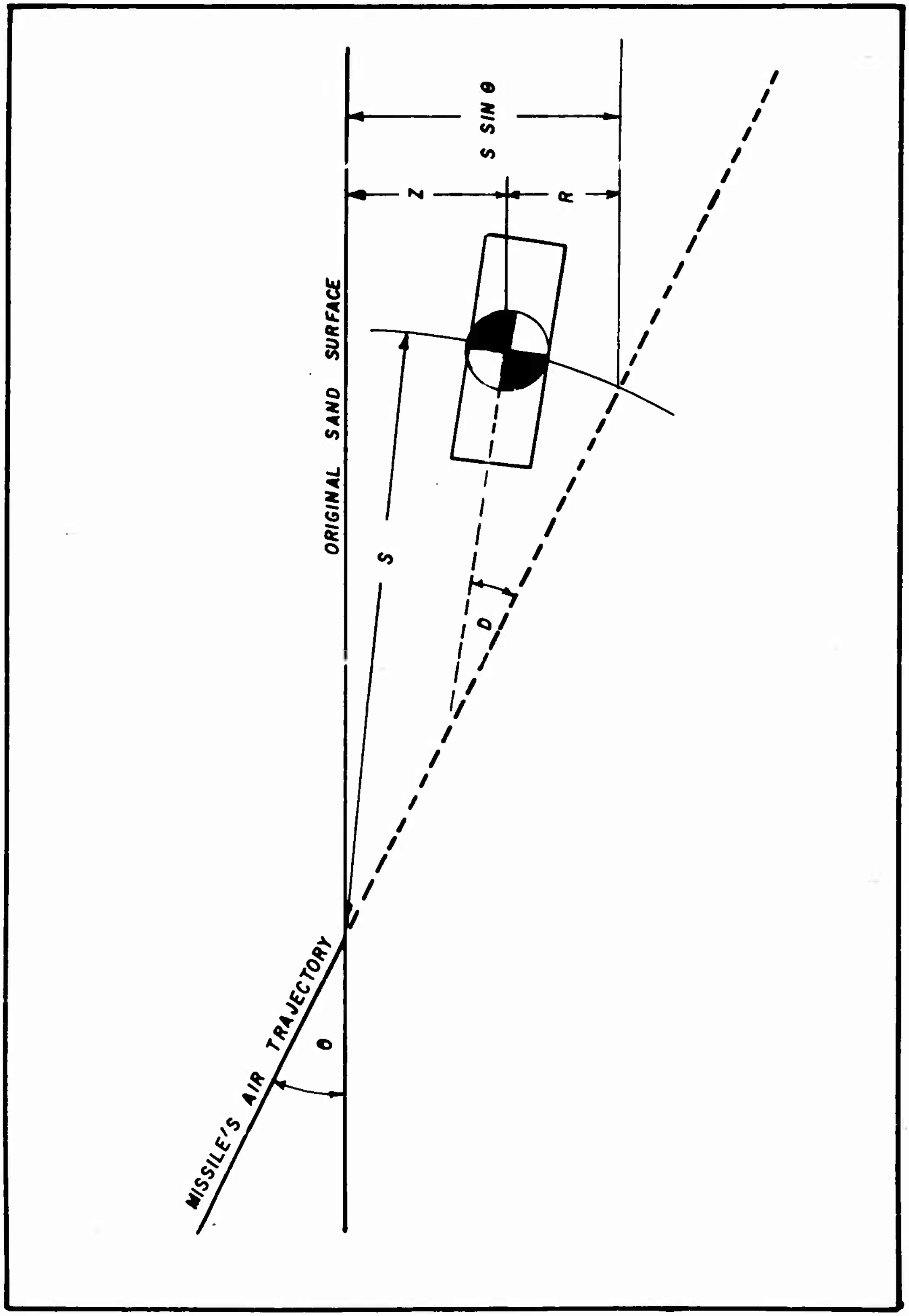

Fig. 16: Definitions

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missiles was obtained by comparing the missile's impact angle, θ, with the orientation of the missile's longitudinal axis in the vertical plane of the axis (see Fig. 16). This quantity is defined as the angular deviation of the missile, D. An upward rotation about the missile's center of gravity was considered positive; and a downward rotation, negative. It was assumed that the angular deviation was always less than 180 deg as there was no way to measure rotations greater than 180 deg. For example, a 190-deg positive rotation would have the same final missile orientation as a 170-deg negative rotation.

Since the depth of penetration is largely dependent on the sine of the impact angle, a new quantity, the rise, R, was defined in order to provide a more convenient parameter for comparing the results at different impact angles (see Fig. 16). This factor, which is measured as $R = S \sin \theta - Z$, represents the rise of the missile above the straight trajectory.

Length of Penetration Vs Impact Angle

The effect of impact angle on penetration length for the C-3 and A-6 missiles is illustrated in Fig. 17 and 18. (The 90-deg penetration data are from Ref. 6). The data obtained for the C-6 missile are presented in Table 20. Fig. 19 is a plot of the individual shots used to determine one of the curves shown in Fig. 17 (C-3 missile at a 20-deg impact angle); the scatter is typical of all the data for the corresponding missiles and conditions.

TABLE 20. PENETRATION DATA FOR C-6 MISSILE

Average Impact Angle (deg)	Average Impact Velocity (fps)	Average Length of Penetration (in.)
20	437	19.4
30	465	18.6
40	456	14.9

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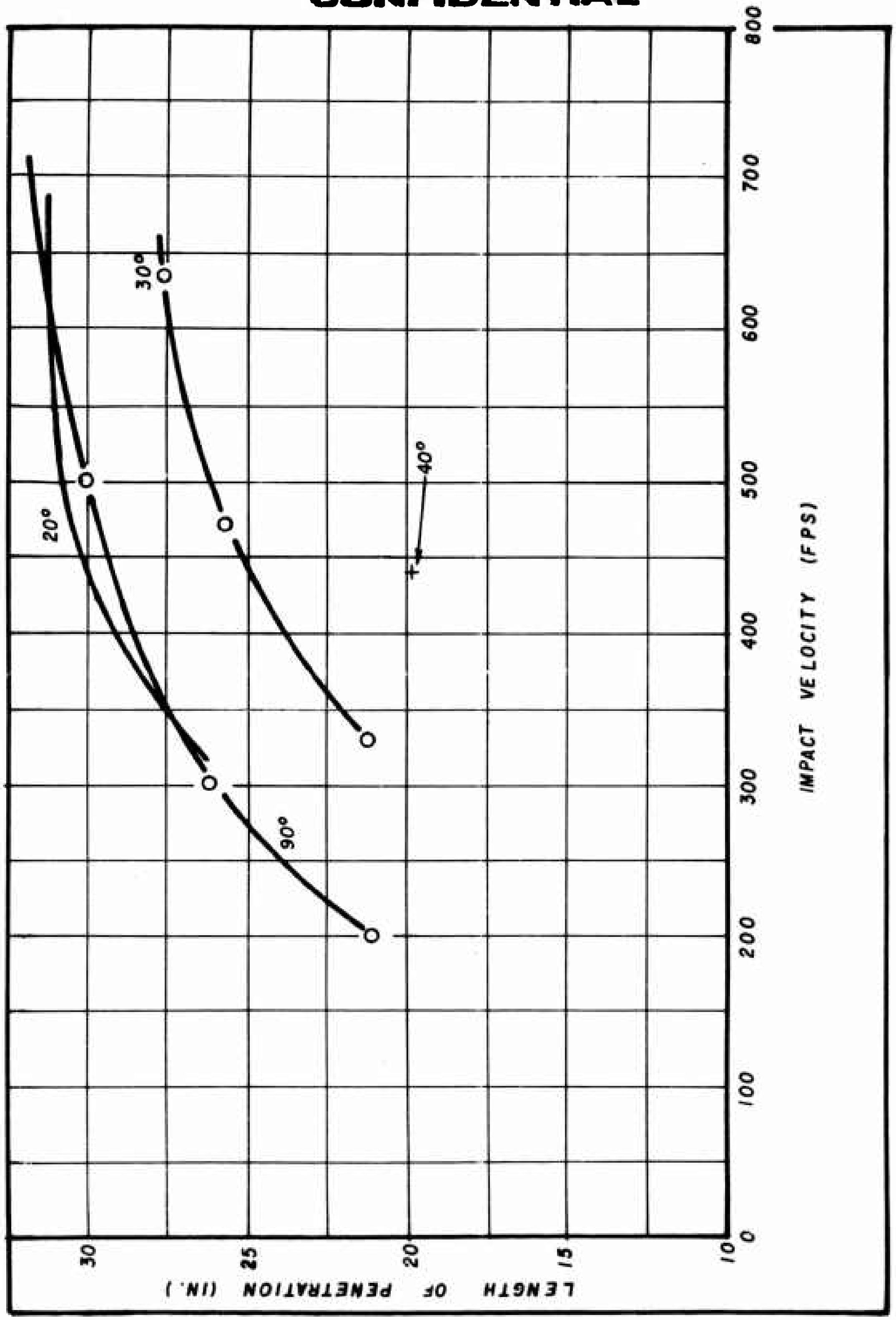

Fig. 17: Effect of Impact Angle on Penetration Length for C-3 Missile

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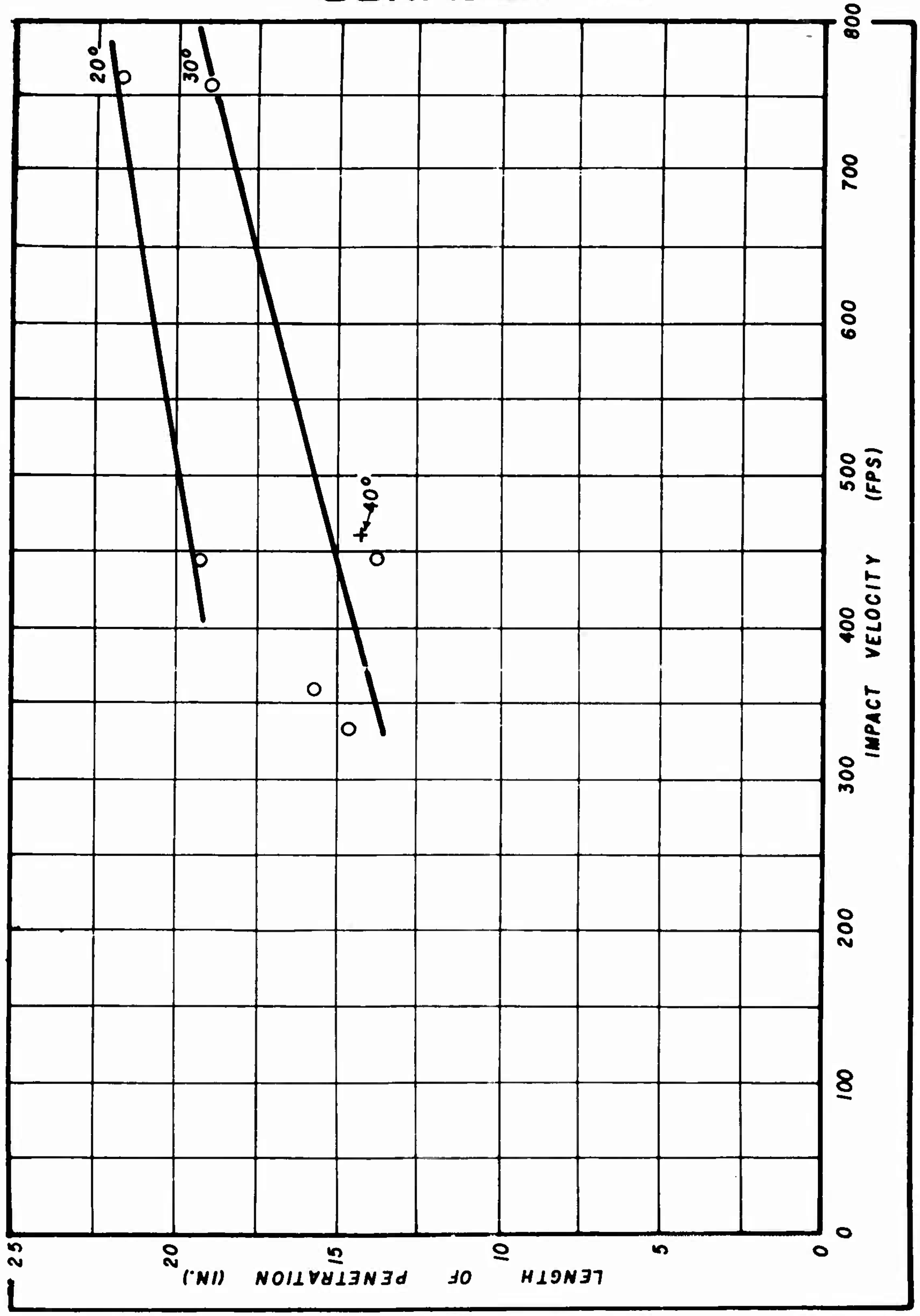

Fig. 18: Effect of Impact Angle on Penetration Length for A-6 Missile

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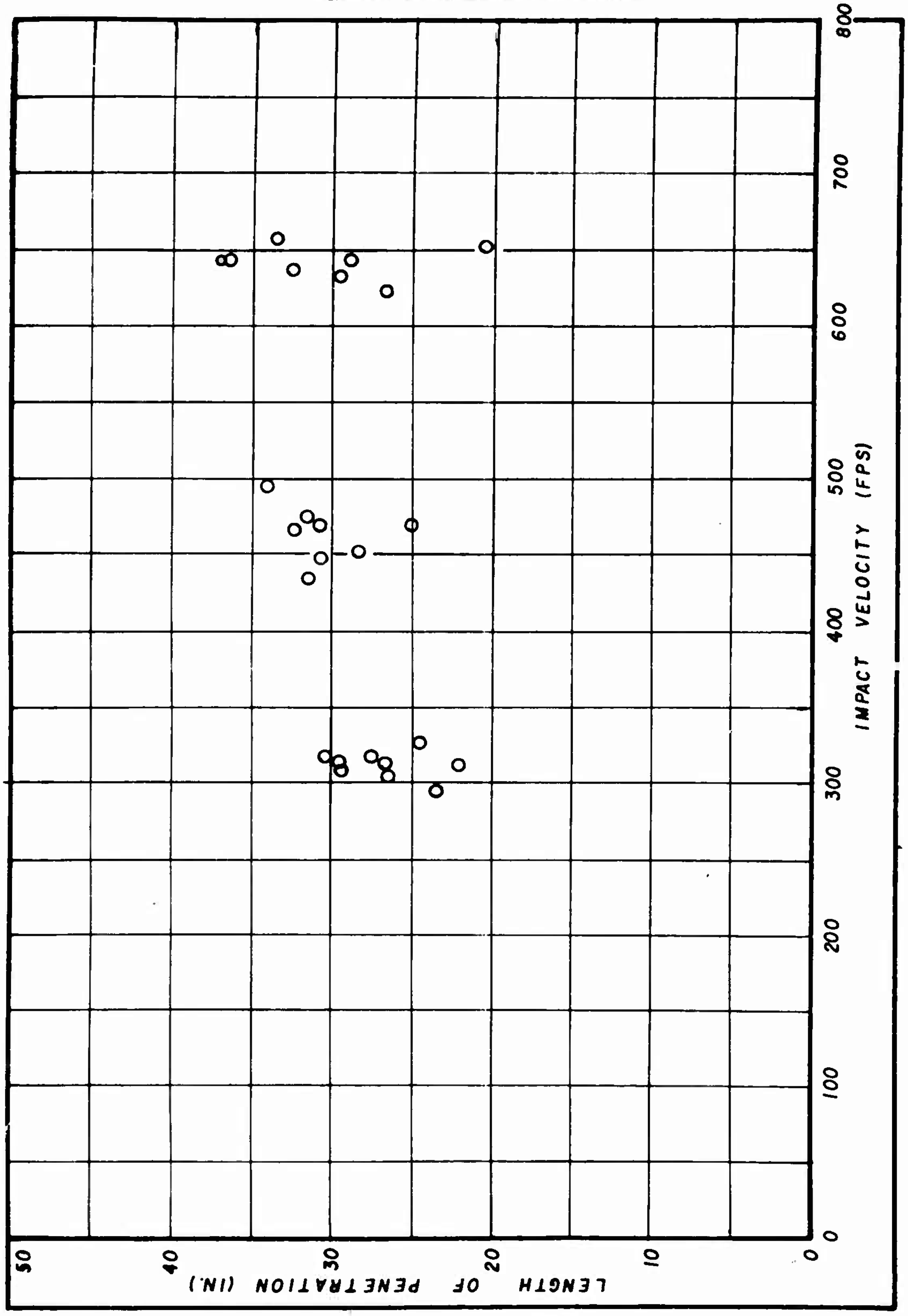

Fig. 13: Data for C-3 Missile Fired at 20-Deg Impact Angle

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If only the acute angles are considered, these data indicate a decrease in penetration length as the impact angle increases from 20 to 40 deg. This effect is explained by an increase in the resistance of the soil with increasing depth. The missiles striking the surface at 20-deg angles travel closer to the surface, where the resistance is low, and thus travel farther. The data for the C-3 at a 90-deg angle, however, reversed this trend; the penetration lengths were about the same as for the 20-deg angles. This suggests that some factor other than a decreased soil resistance near the surface must have affected the penetration.

The primary differences between the penetration of missiles at 90-deg and at acute angles involved the stability of the missiles and the type of trajectory. At 90 deg, the missile followed a relatively straight path with very little oscillation or rotation, while at acute angles the trajectory was curved upward and there were many indications that the missiles oscillated considerably. The latter tendencies would tend to reduce the length of penetration by exposing a greater frontal area to the resistance of the soil.

Depth of Penetration Vs Impact Angle

As indicated by Table 21, each of the three missiles showed an increasing tendency to deviate upward from a straight trajectory as the impact angle was decreased. Hence, the penetration depth, represented by the average rise, increased with decreasing impact angle. If plotted, the average rise is represented as a linear function of the impact angles for the conditions investigated.

Impact Velocity Vs Length of Penetration

The penetration data for all three missiles at 20- and 30-deg impact angles are presented in Fig. 20 and 21. The data are represented on a semi-log plot of

$$\text{impact velocity, } V \quad \text{vs} \quad \frac{\text{penetration length, } S}{\text{missile weight, } W}.$$

There is considerable scatter in the data, but a straight line provides the best-fit experimental curve. This indicates, as previously demon-

TABLE 21. EFFECT OF PENETRATION DEPTH ON IMPACT ANGLE

Missile	Average Impact Angle (deg)	Average Rise Divided by Penetration Length (in./in.)	Average Rise (in.)
A-6	40	0.121	1.75
	30	0.117	1.85
	25	0.186	3.42
	20	0.227	4.65
C-3	40	0.045	0.90
	30	0.065	1.65
	20	0.098	2.90
C-6	40	0.041	0.60
	30	0.097	1.80
	20	0.137	2.65

TABLE 22. PONCELET COEFFICIENT VALUES FOR ACUTE ANGLE PENETRATIONS

Average Impact Angle (deg)	Poncelet Parameters	
	a (psi)	b (lb $sec^2/in.^4$)
90	9.80	17×10^{-5}
30	0.04	25×10^{-5}
20	0.10	17.9×10^{-5}

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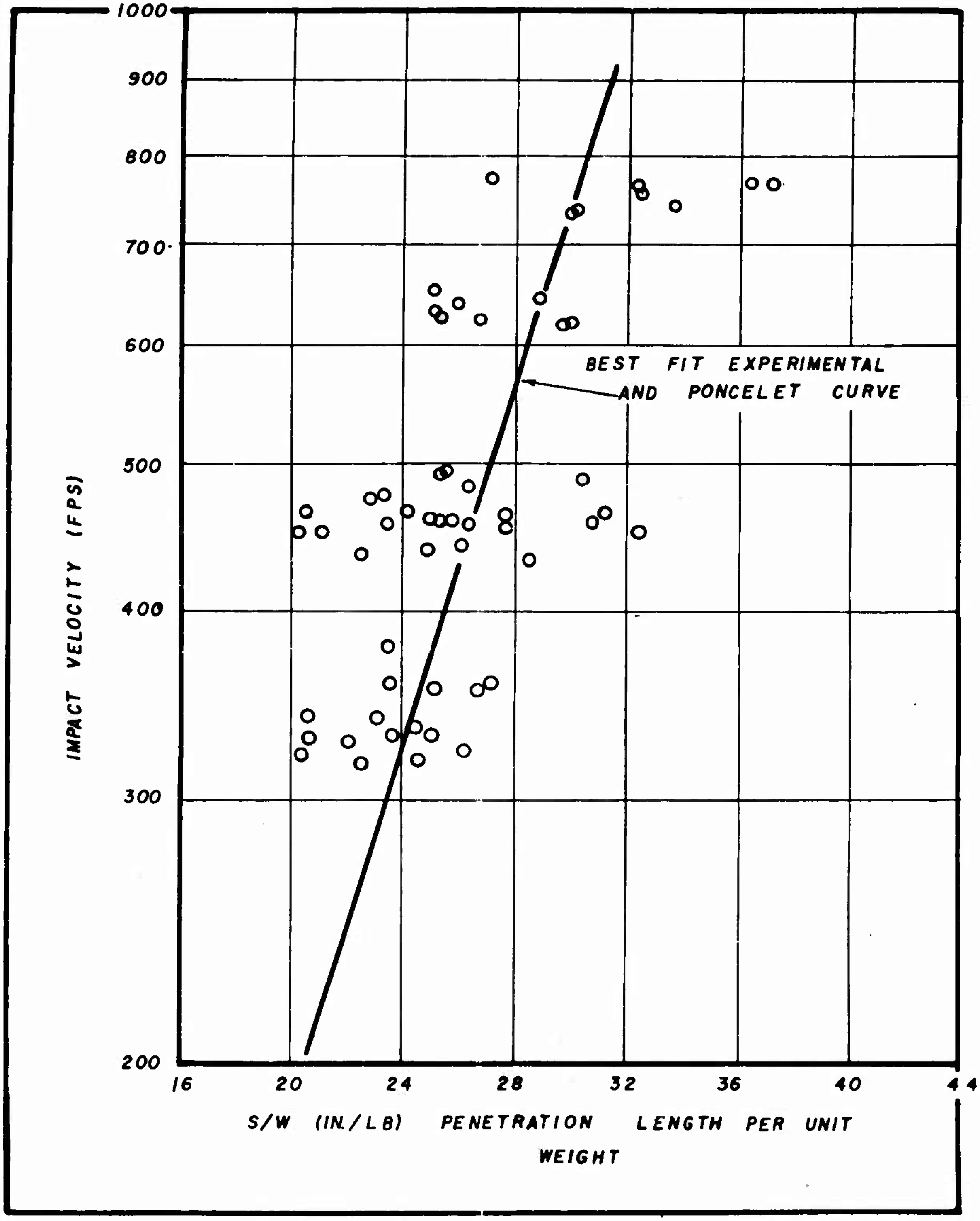

Fig. 20: Penetration Data for 20-Deg Impact Angle

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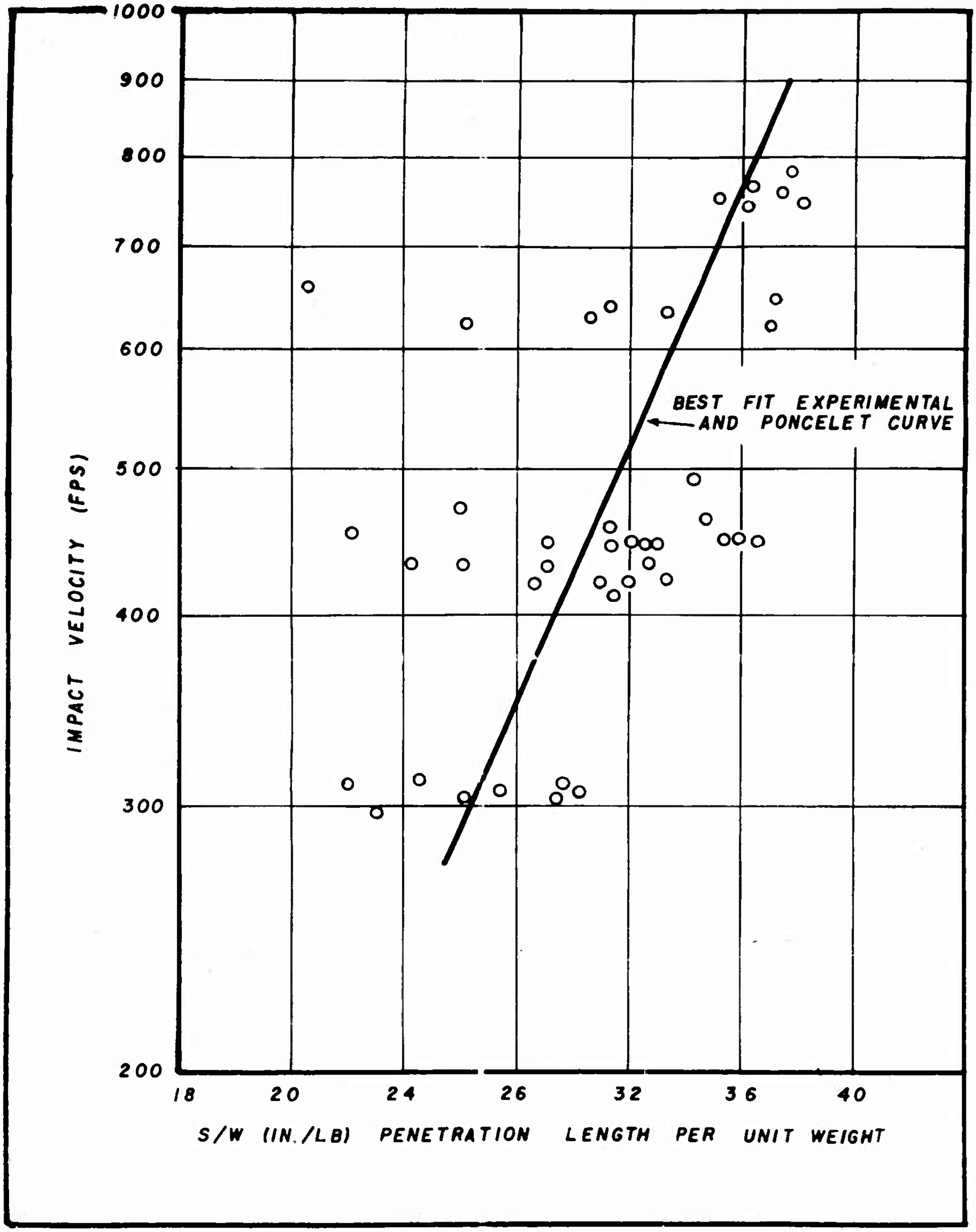

Fig. 21: Penetration Data for 30-Deg Impact Angle

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strated with 90-deg penetration tests (Ref. 6), that the penetration length is proportional to the natural logarithum of the impact velocity.

Calculation of Penetration Length

The Poncelet a and b values determined for 20- and 30-deg impact angles are shown in Table 22. These values were applied to the Poncelet equation which was derived to determine whether penetration can be calculated for missiles entering the ground at acute angles (p. 71). The resultant Poncelet curves are shown in Fig. 20 and 21. As indicated, the best-fit Poncelet curves are equivalent to the best-fit experimental curves. Nevertheless, the Poncelet curves cannot be considered a completely satisfactory method of predicting penetration length because of the wide scatter in the data.

Missile Stability

The relative stabilities of the three missiles tested can be obtained by comparing their average angular deviations:

Missile	Average Angular Deviation (deg)
A-6	-67
C-6	-25
C-3	-5

Since the tests were conducted over approximately the same ranges of impact angles and velocities, these figures were obtained by averaging all the data available for each missile. The comparison indicates that the C-3 is the most stable and the A-6 the least stable; this is probably due to the C-3's greater moment of inertia and length.

The effect of impact angle on missile stability is shown in Table 23. The averages for a given angle are for the entire range of velocities tested. As indicated, the stability of the missiles decreased at the lower impact angles; even the data are not of sufficient quantity to predict this relationship accurately. This trend is reasonable in that the missiles were expected to rotate more as the impact angle approached the range of angles where ricochet normally occurs.

TABLE 23. EFFECT OF IMPACT ANGLE ON MISSILE STABILITY

Missile	Average Impact Angle (deg)	Average Angular Deviation (deg)
A-6	20	-135
	25	-60
	30	-56
	40	-67
C-3	20	-9
	30	0
	40	-7
C-6	20	-71
	30	-24
	40	-9

Full-Size Missiles

The experimental data obtained from these tests can be very useful in predicting the final resting position of a full-size missile. The example considered here is a full-size experimental C-3 missile that has been drop-tested at Eglin AFB, Florida.

On the assumption that the modeling laws relating full-size missiles and scale models (Ref. 5 and 8) are applicable for these acute-angle penetrations experiments, the penetration length can be predicted either from the experimental data (Fig. 18, 19, 20) or from the Poncelet equation (p.71) in which the a and b coefficients are used for the particular angle being investigated. At other angles, results can be obtained by interpolating between the available data. However, care must be taken not to extrapolate to angles lower than 20 deg, at which the missiles tend to ricochet; it is expected that more radical changes would be obtained in this lower range. The penetration depth can be calculated from the average rise, which, in turn, can be predicted only from the experimental values in Table 24.

The following sample calculation is now considered:

Condition	Full-Size C-3 Missile	C-3 Scale Model
Missile Diameter, D (in.)	12.75	1.367
Missile Weight, W (lb)	850	1.010
Impact Angle, Θ (deg)	30	30
Impact Velocity, V (fps)	550	550

From Fig. 18, the penetration length for the C-3 scale model, S_m, is 27 in. for the above conditions. From the modeling laws (Ref. 5 and 8), the true weight of the full-size missile, W_{tf}, is derived as follows:

$$W_{tf} = \left(\frac{D_f}{D_m}\right)^3 W_m \quad \text{or} \quad \left(\frac{12.75}{1.367}\right)^3 \times 1.01 = 810 \text{ lb.}$$

However, since the actual weight of the full-size missile, W_{af}, is 850 lb, a slight correction must be made for the deviation. According to the modeling laws, the predicted penetration length for the full-size missile, S_f, is derived as follows:

$$S_f = \frac{D_f}{D_m} \times \frac{W_{af}}{W_{tf}} \times S_m \quad \text{or} \quad \frac{12.75}{1.367} \times \frac{850}{810} \times 27 = 264 \text{ in.}$$

From Table 21, the ratio of the average rise of the scale model, R_m, to the penetration depth of the scale model, S_m, is 0.065. The average rise of the full-size model, R_f, is derived as follows:

$$R_f = R_m \times S_f \quad \text{or} \quad 0.065 \times 264 = 17.0 \text{ in.}$$

The penetration depth of the full-size missile, Z_f, is derived as follows:

$$Z_f = S_f \times \sin \Theta - R_f \quad \text{or} \quad 264 \times \sin 30 - 17.0 = 115 \text{ in.}$$

DERIVATION OF PENETRATION FORMULA FOR ACUTE ANGLES

It is assumed that the Poncelet Force Law for the soil resistance, r, per unit area is given by

$$r = (a + b\dot{x}^2), \tag{1}$$

where $\dot{x}$ is the variable missile velocity. Thus, the total resistance, F, is given by

$$F = Ar = A(a + b\dot{x}^2). \tag{2}$$

For acute angle penetrations,

$$m\dot{x} \frac{d\dot{x}}{dx} = A(x)\ (a + b\dot{x}^2), \tag{3}$$

where x is the variable length of penetration. The result of separating variables and integrating is

$$m \int_{V_o}^{\dot{x}} \frac{\dot{x}d\dot{x}}{(a + b\dot{x}^2)} = -\int_0^x A(x)dx\ . \tag{4}$$

For a blunt-nosed cylinder (see Fig. 22),

$$A(x) = 2\int_0^y (2ry - y^2)^{\frac{1}{2}}\, dy$$

$$A(x) = \frac{\pi r^2}{2} + (y - r)\ (2ry - y^2)^{\frac{1}{2}} + r^2 \sin^{-1}\left(\frac{y-r}{r}\right). \tag{5}$$

If a straight trajectory is assumed,

$$y = x \tan \theta\ . \tag{6}$$

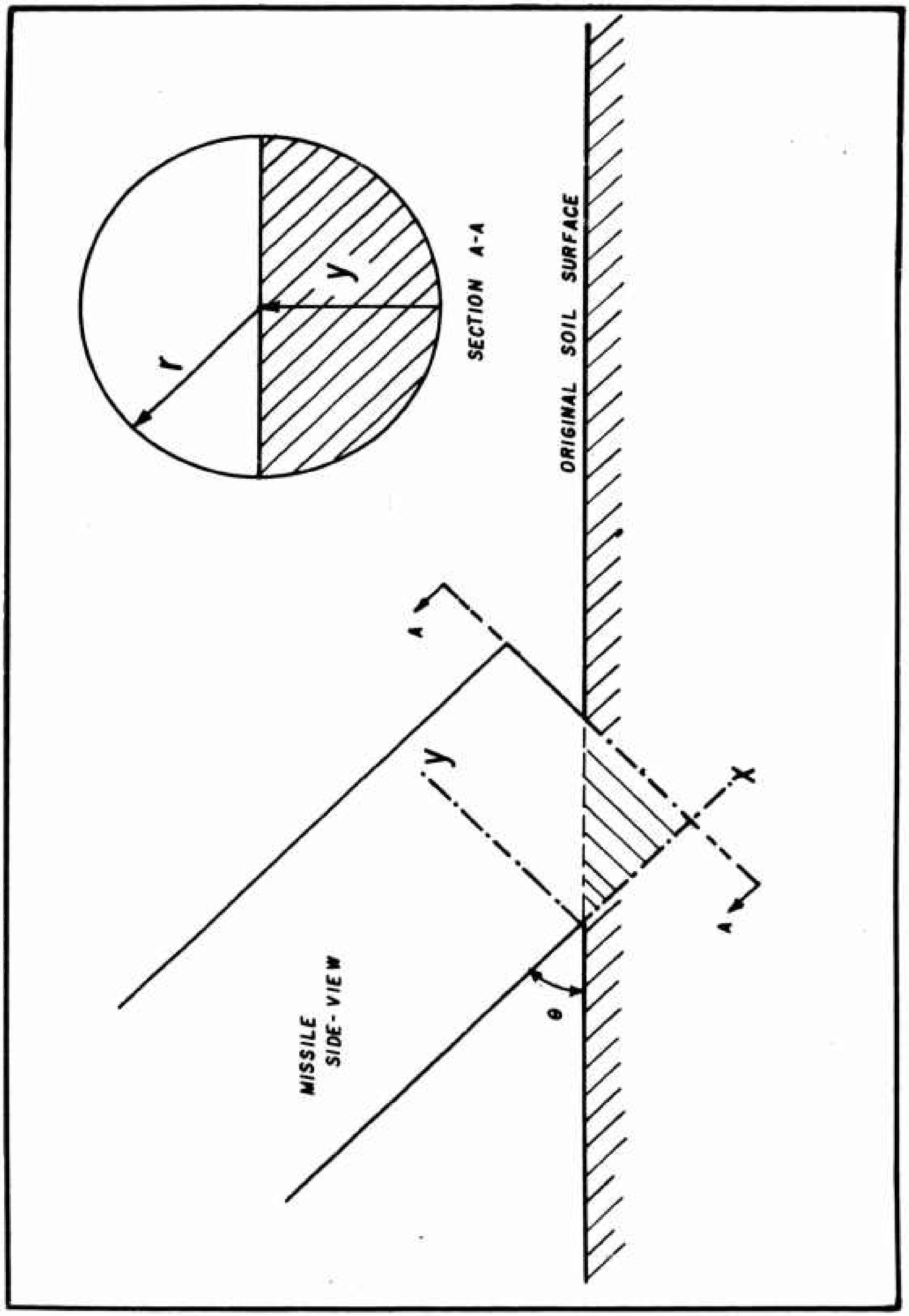

Fig. 22: Blunt-Nosed Missile Striking Earth

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Substituting (6) into (5) results in

$$A(x) = \frac{\pi r^2}{2} + (x \tan \theta - r)\,(2rx \tan \theta - x^2 \tan^2 \theta)^{\frac{1}{2}}$$

$$+ r^2 \sin^{-1}\left(\frac{x \tan \theta - r}{r}\right) . \qquad (7)$$

Substituting (7) into (4) and performing the integration results in

$$\frac{m}{2b} \ln\left(\frac{a + b\dot{x}^2}{a + bV_o^2}\right) = -\frac{\pi r^2 x}{2} + \frac{\tan^{\frac{1}{2}} \theta}{3}\,(2rx - \tan \theta x^2)^{3/2} - \frac{r^3}{\tan \theta}$$

$$\left(u \sin^{-1} u + \sqrt{1 - m^2} - \frac{\pi}{2}\right) , \qquad (8)$$

where

$$u = 1 - \frac{x \tan \theta}{r} .$$

For a complete burial of the nose where $x = x_1$,

$$x_1 = 2r \operatorname{ctn} \theta \qquad (9)$$

Substituting (9) into (8) and simplifying results in

$$(a + b\dot{x}_1^2) = (a + bV_o^2)e^{\frac{-2\pi\, br^3}{m \tan \theta}} \qquad (10)$$

In sand soils during the early portion of the trajectory

$$a < < b\dot{x}^2 \quad \text{(see Ref. 6).} \qquad (11)$$

Substituting (11) into (10) results in

$$\dot{x}_1^2 \approx V_o^2 \, e^{\frac{-2\pi\, br^3}{m \tan \theta}} \qquad (12)$$

In Ref. 6, the equation for the length of penetration for $A(x) =$ constant in sand soils was derived as

$$S = \frac{m}{2BA} \ln\left(\frac{b}{a} V_o^2\right) . \qquad (13)$$

The result of substituting $V_o = \dot{x}_1$ into (13) and adding the length of penetration to x_1, the point where complete contact occurred, is given by

$$S = \frac{m}{2BA} \ln\left(\frac{b}{a} V_o^2 \bullet \frac{-2\pi b r^3}{m \tan \Theta}\right) + 2r \operatorname{ctn} \Theta, \tag{14}$$

This can be simplified to

$$S = \frac{m}{bA} \ln\left(\frac{b}{a} V_o\right) + \frac{r}{\tan \Theta} \cdot \tag{15}$$

TABLE 24. RICOCHET AND PENETRATION DATA

Missile	Impact Angle (deg)	Impact Velocity (fps)	[a]Length of Penetration (in.)		[b]Depth of Penetration (in.)	
			To Nose	To Tail	To Nose	To Tail
C-3	20	309	33.0	29.0	5.8	6.5
		295	25.0	23.0	7.8	3.0
		311	22.5	21.2	8.5	1.8
		305	29.0	23.0	7.8	5.5
		324	26.0	22.0	8.7	4.0
		312	33.0	25.0	6.5	7.0
		319	30.0	24.0	8.0	5.5
		320	24.0	26.0	7.5	6.8
C-3	20	435	35.0	27.5	8.5	7.0
		476	34.5	27.5	8.2	6.2
		469	26.5	23.0	9.5	3.8
		497	38.0	29.5	7.8	7.8
		469	34.5	27.0	8.0	6.5
		467	36.5	28.5	8.5	7.5
		448	34.0	27.0	8.5	6.3
		452	30.5	25.5	9.0	5.0
C-3	20	662	17.0	23.5	11.0	3.5
		633	31.0	26.5	12.5	6.0
		637	35.5	29.0	10.0	6.5
		625	27.0	25.0	12.0	4.5
		645	29.0	27.0	13.0	5.0
		645	40.0	33.0	9.5	8.0
		667	35.0	32.0	9.5	4.0
		645	40.0	33.0	9.0	7.0

[a]Length of penetration to missile center of gravity was calculated from these data.

[b]Depth of penetration to missile center of gravity was calculated from these data.

(Table 24., Cont.)

Missile	Impact Angle (deg)	Impact Velocity (fps)	Length of Penetration (in.)		Depth of Penetration (in.)	
			To Nose	To Tail	To Nose	To Tail
C-3	30	330	25.0	17.5	11.8	9.0
		334	21.0	16.5	13.0	6.5
		331	25.0	16.5	9.5	8.8
		320	25.0	16.5	10.8	8.5
		311	25.0	17.5	11.5	8.5
		342	22.0	15.0	11.8	7.5
		340	26.5	17.5	10.8	9.0
		335	22.0	16.0	11.5	7.2
C-3	30	440	27.0	19.5	13.5	9.5
		460	26.0	19.5	14.0	8.5
		467	29.0	20.5	14.0	11.0
		471	29.0	21.0	13.0	11.0
		497	27.5	21.0	14.0	9.5
		483	26.0	20.0	14.0	9.0
		469	25.0	19.0	13.5	8.5
		476	24.5	16.5	13.0	8.5
C-3	30	641	30.5	22.0	14.5	11.0
		621	28.0	21.0	14.5	10.5
		637	25.5	20.0	15.0	8.5
		629	31.5	23.5	13.5	10.5
		621	31.5	24.0	12.5	11.0
		645	26.5	20.0	14.0	9.0
		633	26.0	20.0	13.5	8.5
		649	26.0	19.0	14.5	8.5
C-3	40	457	18.0	12.5	14.5	9.5
		452	15.0	14.0	16.5	8.0

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(Table 24., Cont.)

Missile	Impact Angle (deg)	Impact Velocity (fps)	Length of Penetration (in.)		Depth of Penetration (in.)	
			To Nose	To Tail	To Nose	To Tail
C-3	40	444	13.5	13.5	15.0	9.5
		405	18.5	14.0	15.0	7.5
		438	20.0	12.5	13.5	9.5
		431	19.0	13.5	15.0	10.0
		446	18.5	15.0	15.0	9.5
		431	21.0	15.0	15.5	11.0
A-6	20	446	16.5	21.0	4.0	1.5
		446	16.0	20.5	3.5	2.0
		444	19.0	21.5	6.0	2.5
		435	17.5	20.0	3.5	2.5
		422	17.0	21.5	2.5	1.0
		427	16.5	20.5	3.5	2.5
		450	17.5	22.5	2.0	0.8
A-6	20	763	19.0	22.5	3.0	1.5
		757	19.0	23.0	3.0	1.0
		757	19.0	23.0	3.5	1.5
		757	20.0	24.0	3.0	1.3
		763	19.0	23.0	4.0	2.0
		757	20.0	24.5	3.0	1.0
		757	20.0	24.0	2.5	1.0
A-6	25	347	12.5	17.0	5.0	2.5
		366	15.5	16.5	7.0	3.5
		368	13.0	16.5	6.0	3.0
		365	12.5	15.5	6.0	3.0
		364	14.0	16.5	7.0	3.2
		350	14.0	16.5	6.2	3.0

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(Table 24., Cont.)

Missile	Impact Angle (deg)	Impact Velocity (fps)	Length of Penetration (in.)		Depth of Penetration (in.)	
			To Nose	To Tail	To Nose	To Tail
A-6	25	338	14.0	15.5	6.5	3.0
		350	12.5	16.0	5.5	2.5
		450	22.0	15.8	2.3	4.5
		452	18.4	18.0	2.8	3.8
		431	18.6	17.0	4.0	4.8
		437	13.4	17.5	4.4	2.1
		438	23.0	19.5	1.5	5.0
A-6	30	333	12.0	15.5	7.0	3.5
		316	15.5	12.5	7.0	5.5
		318	12.0	15.0	6.5	3.0
		355	13.5	14.5	7.5	4.0
		307	12.5	15.0	6.5	3.0
		351	14.5	15.0	8.0	3.0
		364	11.0	15.0	6.0	3.0
		337	13.5	12.5	7.5	5.0
A-6	30	467	13.5	12.5	8.5	4.5
		450	9.5	11.5	6.5	4.5
		437	9.5	12.5	7.5	3.5
		440	11.5	13.0	8.5	3.5
		427	17.5	14.5	2.0	5.5
		454	15.5	11.5	6.0	7.0
		435	10.5	14.0	6.5	3.5
		463	13.5	9.0	4.5	4.0
A-6	30	769	13.0	17.0	4.5	
		757	16.0	19.0	9.0	5.5
		757	16.5	20.0	9.5	5.5
		741	15.0	18.0	8.5	5.5

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(Table 24., Cont.)

Missile	Impact Angle (deg)	Impact Velocity (fps)	Length of Penetration (in.) To Nose	Length of Penetration (in.) To Tail	Depth of Penetration (in.) To Nose	Depth of Penetration (in.) To Tail
A-6	30	741	15.0	19.0	7.5	4.5
		757	21.5	19.0	8.0	8.5
		757	19.0	18.0	9.5	6.0
		763	18.0	17.5	8.0	6.0
A-6	40	488	11.5	13.5	10.0	5.5
		461	11.5	13.0	10.0	5.0
		442	15.0	11.0	8.0	8.5
		446	10.0	14.0	8.5	5.5
		500	10.5	11.5	10.5	6.5
		435	9.0	12.0	8.5	5.5
		454	9.5	12.0	9.5	5.5
		469	10.0	12.0	10.0	5.0
C-6	20	435	19.0	19.0	7.0	3.5
		433	13.5	18.5	4.5	2.0
		490	14.5	19.0	6.0	2.0
		478	27.0	22.5	3.5	4.5
		467	15.0	19.5	5.0	2.0
		433	21.5	20.5	5.5	2.5
		435	16.5	21.5	2.5	1.0
C-6	30	450	23.0	14.0	8.0	7.8
		476	13.0	15.0	9.5	4.0
		465	22.5	16.5	8.5	7.5
		467	21.0	18.0	9.0	6.5
		457	14.0	17.0	9.5	4.5
		454	13.0	16.0	9.0	4.0
		488	16.0	16.0	10.5	5.5
		469	20.0	18.0	9.5	6.5

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(Table 24., Cont.)

Missile	Impact Angle (deg)	Impact Velocity (fps)	Length of Penetration (in.)		Depth of Penetration (in.)	
			To Nose	To Tail	To Nose	To Tail
C-6	40	422	16.0	10.5	10.0	8.0
		461	16.0	11.5	11.0	8.0
		454	16.0	11.5	10.0	8.5
		420	11.0	11.0	10.5	5.5
		446	11.0	11.5	10.5	6.0
		413	16.0	11.0	10.0	8.0
		446	15.0	12.0	10.5	7.5
		433	16.5	11.5	9.5	9.0

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